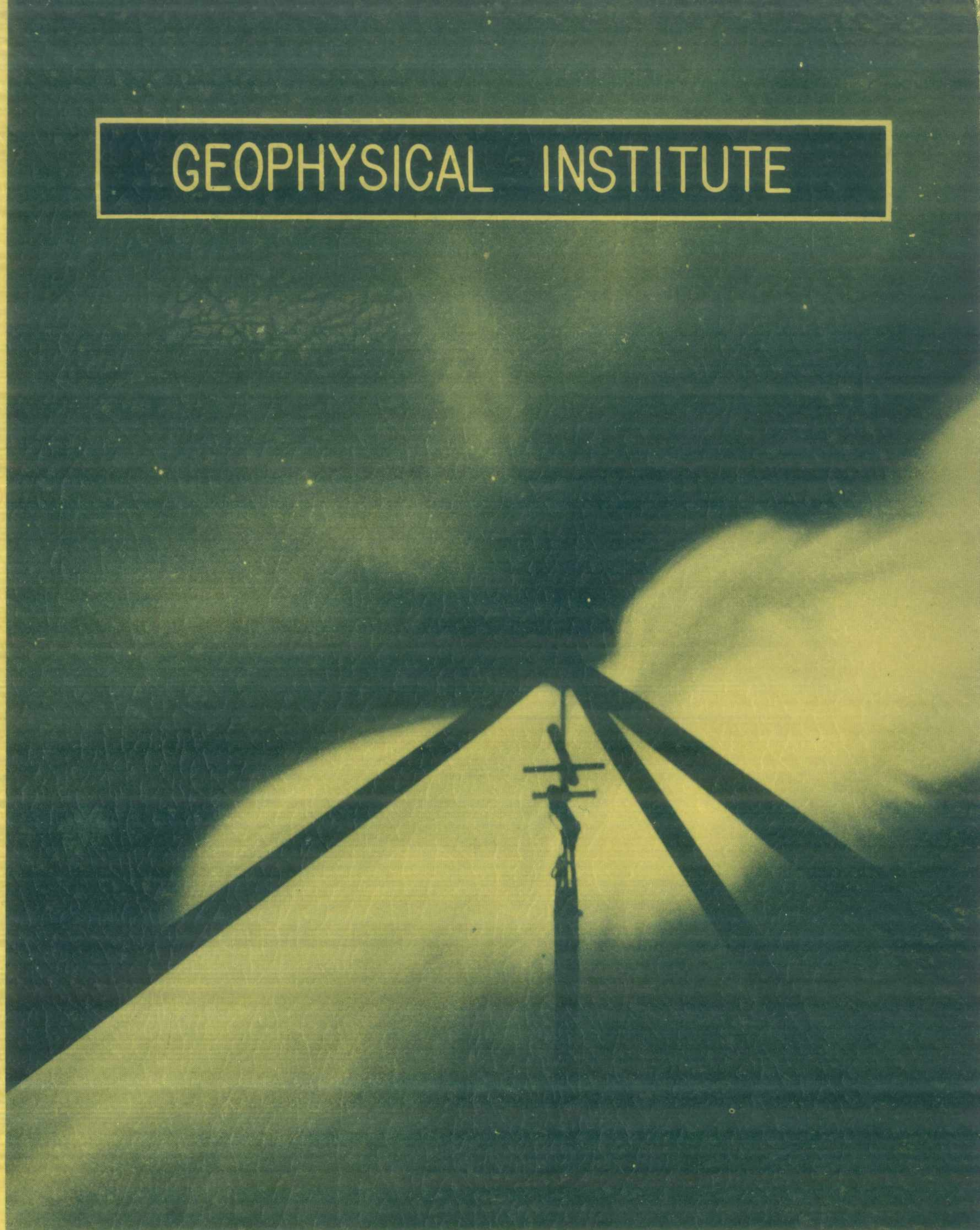

UNIVERSITY
OF ALASKA

COLLEGE
ALASKA

UAG-R116

DISTRIBUTION OF RADAR AURORAS OVER ALASKA

by

Robert S. Leonard

Scientific Report No. 9
NSF Grant No. Y/22.6/327
April 1961

GEOPHYSICAL INSTITUTE

of the

UNIVERSITY OF ALASKA

Scientific Report No. 9

DISTRIBUTION OF RADAR AURORAS OVER ALASKA

by

Robert S. Leonard

NSF Grant No. Y/22.6/327

Submission Date:

April,1961

Principal Investigator:

C. T. Elvey

C. T. Elvey
Director

PREFACE

The object of the present work was to investigate the distribution of radar aurora in latitude and time by means of a chain of identical radar systems with overlapping coverage. The location and extent of the visual auroral zone was carefully investigated previously, but no companion study existed for the radar aurora. Previous studies of radar reflections from the aurora were carried out from one station at a time with radars of widely different characteristics. These circumstances defeated all attempts to connect the various observations into a synoptic pattern. The present investigation has a practical application as the radar aurora is a possible means for extending radio communications beyond the line of sight. Prior to this study, however, no direct information was available concerning the duration of suitable auroral echoes.

The material is presented in the following manner:

CHAPTER I gives a summary of the previous radar investigations of the aurora, stressing results which aid in the analysis of the data collected in this experiment.

CHAPTER II contains a description of the equipment located at each field station and a review of the method of operation. The influence of the equipment on the data and the operational procedures are discussed. The design of a unique, semi-automatic scaling machine, developed at the Geophysical Institute to expedite the scaling of the 50,000 feet of data-film, is presented, followed by a description of the method employed to scale the films.

CHAPTER III presents the results of the analysis in two main sections. The first section is devoted to a study of the distribution of echo occurrence with range. The distribution of the occurrences from each station is followed by a superposition of this same data to show the radar auroral zone. Under certain conditions this zone can be interpreted as a zone of ionospheric disturbances. The effects of magnetic disturbances on this zone are shown. In the second section, the diurnal pattern of echo occurrence is given. Anomalies in these diurnal patterns are noted and an interpretation is given in terms of ionospheric parameters.

CHAPTER IV summarizes the results of this work and includes suggestions for subsequent studies.

*

TABLE OF CONTENTS

*

LIST OF FIGURES

LIST OF TABLES

*

ABSTRACT

Analysis of data collected by five auroral radars located in Alaska shows the distribution of ionospheric disturbances as a function of time and location. The radars were operated during the IGY and were located in a nearly straight line running magnetically north-south across Alaska; these locations made it possible to observe disturbances continuously in the range, from 60 to 80 degrees geomagnetic latitude, which includes the visual auroral zone.

An apparent radar auroral zone with a maximum at 67 degrees geomagnetic latitude is indicated by this study. The decrease in occurrence to the south of this maximum is verified, but the decrease to the north can not be accurately defined as the roll of aspect sensitivity is not fully understood. The radar auroral zone spreads to the south during increased magnetic disturbance, and some indication is found of a lessening of activity well north of the visual auroral zone. A conclusion is also reached that the layer causing radio wave absorption during aurora is not uniform but contains "holes" or regions of low absorption.

The diurnal occurrence curves indicate two principal maxima. One is observed at all stations at times near local midnight. The time of the other maximum depends on the latitude of observation; it is later in the morning at the more northern locations. These two echoes exhibit differing degrees of aspect sensitivity, the morning echoes having a narrower scattering polar diagram.

CHAPTER I

RADAR STUDIES OF THE AURORA

The influence of the aurora or northern lights on radio waves has been recognized for some time. Radio amateurs discovered during the 1930's that they were able to communicate abnormally long distances on frequencies too high to be propagated by normal modes. The effect was associated with the aurora because it was most commonly noticed at times of visual aurora displays. The amateurs found it necessary to direct the antennas at both stations toward the aurora rather than toward each other (Moore, 1951).

Following World War II, many of the advances made in radar during the war were applied to ionospheric research. In England, a VHF (Very High Frequency*) radar, operated for meteor trail observation, detected an enhancement of background noise which was associated with a visible aurora (Lovell et al, 1947); this was the first reported detection of the aurora by means of radar. Herlofson (1947) discussed this observation as being caused by a reflection at a fairly sharp boundary in electron density associated with the southern boundary of the visual aurora form. He suggested that it was necessary to view this form nearly normal to its face in order to receive an appreciable signal.

---

*The term Very High Frequency is used to denote that portion of the radio spectrum lying between 30 and 300 Mc/s; the term Ultra High Frequency is similarly associated with the portion between 300 and 3000 Mc/s.

Following this discovery, many others began investigations of natural radar echoes and began associating them with other manifestations of high latitude disturbances. Harang and Landmark (1954), making observations on 35 and 74 Mc/s, concluded that there was no direct correlation in occurrence between the echoes and the visual aurora. Subsequent investigations between 30 and 72 Mc/s ran the gamut between fairly good correlation (Hellgren and Meos, 1952; Bullough and Kaiser, 1955; and Lyon, 1960) to no direct correlation (Gadsden, 1959). The experiment covered by this report did not investigate this facet of the radar echoes. In an attempt to avoid this uncertainty of correlation, the term aurora will be used to mean radio aurora unless it is specified to mean visual aurora.

All of the early radar experiments were in generally good agreement as to the experimental results. Echoes could only be obtained when the radar was directed at fairly low elevation angles and toward the magnetic pole; as the stations were all located fairly far south of most auroral disturbances, this distribution of echoes could be attributed to a lack of aurora elsewhere in the field of view of the radar. Several experiments were mounted to beam the radar into the sky directly overhead. The results were in good agreement; no echoes could be detected despite many occurrences of visual aurora directly overhead. These results were interpreted differently by three groups: absorption directly under the visual aurora was assumed by Currie et al (1953); insufficient ionization to refract the waves at short ranges (skip zone effect) by Harang and Landmark (1954); and aspect sensitivity in which the strongest returned signal would occur when the radar ray was normal to the earth's magnetic field in the disturbance as postulated by Booker et al (1955).

Dyce (1955a) tested these three divergent theories with a 51.9 Mc/s radar located at Barrow, Alaska, so that many disturbances occurred far south of the equipment; the result was that extremely few echoes were detected to the south. This supported the theory that echoes were only obtained when the ray from the radar was nearly normal to the earth's magnetic field, a condition that has become known as the "aspect sensitivity" of the auroral echoes. Realizing that the visual auroral forms are closely aligned with the earth's magnetic field, this condition is similar to the condition first proposed by Herlofson (1947).

Unwin (1958) further supported the aspect sensitivity theory by investigating the distribution of echoes on a 55 Mc/s radar with azimuth. The experiment was conducted from the southern tip of South Island, New Zealand, which has a fortunate location in that the contour of zero off-perpendicular angle between the ray from the radar and the magnetic field in the E layer forms a closed curve within the field of view of the radar. Many examples were found in which the echoes were detected in a curve similar to the zero off-perpendicular angle contour but not elsewhere in the field of view of the radar. These results must be regarded as further support for the aspect sensitivity of the auroral echoes.

Booker (1956) developed a theory of back-scattering by nonisotropic irregularities in electron density that were elongated in the direction of the magnetic field. These irregularities were found to be far too small to be associated with a similar visual auroral form, referred to as rays, but were found to be of about the size that could be produced by turbulent motions in the E layer. Later work (Howells, 1959) shows that turbulent motions are not an acceptable means of creating these irregularities, but does not preclude their existence. Owren (1960) has investigated the application of the Booker theory to VHF radar results and comes to the following conclusions:

> There are two implicit assumptions in the theory that must be borne in mind; 1) The refractive index of the medium must be nearly equal to one, and 2) The relative deviation of the electron density $\frac{\Delta N}{N}$, as well as the average electron density, N, must be statistically uniform over the scattering volume.

The first assumption requires that the observing frequency must be appreciably higher than the critical frequency associated with the electron density. Recent observations based on the luminosity of the visual auroral forms imply electron densities in the range of 10^{12} to 10^{14} el/m^3 or critical frequencies between 10 and 100 Mc/s (Murcray, 1960). The second assumption requires that the observations be made in reasonably small regions, implying a very narrow beam radar.

The experiment reported here was performed with radars operating on 41 Mc/s and using a wide antenna beamwidth; therefore any application of this theory to the data presented must be regarded with considerable caution.

A feature of the auroral echoes that has been noticed by many others is that the echoes can be divided into subgroups depending on their behavior or appearance. Aspinall and Hawkins (1950) observing with a 72 Mc/s radar refer to two groups, discrete and diffuse. Their radar transmitted pulse pairs, separated by about 45 km; if the auroral echo resolved these pulse pairs it was classified as discrete, and if the echo blurred them into a single echo, it was classified as diffuse. Hellgren and Meos (1952) followed this scheme but because they were operating a radar that transmitted only single pulses, they relied on the width or depth in range of the echo on the recording oscilloscope to make the distinction. Bullough and Kaiser (1954) also utilized the method of Hellgren and Meos but added additional subclasses of echoes; those that were stationary and those that moved in range.

Observations made at College in the upper VHF and lower UHF ranges (Presnell et al, 1959) were classified into two groups, also labeled discrete and diffuse, but with a different meaning attached to these classes. Their observations were made with a large, steerable antenna giving a small beamwidth, which enabled them to trace out the shape of the echoing region in space. Their echoes were classed as discrete if they came from an echoing region that was well defined in space and oriented perpendicularly to the radar beam so that scans in elevation did not reveal any range shift. The other type, diffuse, were from echoing regions that were of large extent so that scans in elevation showed a range shift; this range shift with elevation changes was of the proper sense and magnitude to trace out a "cloud" or layer roughly parallel to the earth's surface at approximately E layer heights. Bates (1961) operating an oblique HF sweep-frequency sounder at College reported an echo which correlates with echoes on the 41 Mc/s auroral radar but which arises in an extended layer possessing similar properties to the layer associated with the diffuse echo observed on the VHF-UHF radar.

Unwin (1959) identified two types of echoes, discrete and diffuse, but further sub-divided each one into two sub-groups based either on their duration or their structure as determined by examining the range-time* film. As the experimental parameters are quite different it is difficult to associate directly these echo classifications with those from the VHF-UHF experiment (Presnell, 1959). In addition to identifying these 4 echo types, Unwin (1959) was able to make very careful measurements of the height of the echoing

*Range-time recording on film implies that the range to the echo is measured across the film strip, and the time of day along the film; this is the most common type of recording used in these experiments.

regions and their thickness for each type of echo. The results of this study show that almost all of the echoes occur between 100 and 120 km height with a maximum at 110 km. This maximum is in agreement with other, less accurate, work done in the northern hemisphere (Currie, Forsyth and Vawter, 1953; and Presnell et al, 1959).

Many authors have investigated the diurnal behavior of the auroral echoes (Bhattacharyya, 1960; Bullough and Kaiser, 1955; Currie et al, 1953; Hellgren and Meos, 1952; Lyon, 1960; Presnell et al, 1959; Unwin, 1959). There is one point of agreement, a general maximum of occurrence near local midnight. From this point on there is little agreement, however; some list a secondary maximum early in the evening around 1800, others place it somewhat later, while others do not show it at all. The same holds true in the morning where times of the secondary maxima range between 0300 and 0900, or are not shown at all.

In addition to the diurnal behavior of the echoes, most of these authors show the distribution of echoes as a function of range and azimuth from their station. By selecting the azimuth of the magnetic meridian, this data gives the distribution of echoes with latitude. Unfortunately, these observations have all been made from only one station at a time and the distribution of echoes with latitude is strongly influenced by the variation in sensitivity of the radar with range. The simple radar equation applicable to small targets

$$P_r = \frac{P_t G^2 \lambda^2 \sigma}{64\pi^3 R^4} \tag{1}$$

P_r = Received power
P_t = Transmitted power
G = Antenna gain
λ = Wavelength
σ = Scattering area
R = Range

gives an exponent of -4 for the dependence on range of the radar sensitivity. If the target fills the beamwidth of the radar antenna, the scattering area, σ, will be dependent on the range, and the sensitivity will obey an R^{-3} law. Likewise, if the vertical extent is also dependent on the range, the sensitivity will obey an R^{-2} law. Seed (1958) experimentally determined the exponent as being very close to -2.

1.1 Summary

The auroral echoes have been shown to be aspect sensitive to such a degree that they can only be observed when the ray from the radar is within a few degrees of perpendicularity to the magnetic field in the echoing region. The echoes originate very close to a 110 km height and their association with visual aurora is not clear. The echoes can be divided into various classes based on different aspects of their behavior, but no consistent pattern can be developed among the various observations. The echoes are known to occur most frequently near local midnight but there is little agreement as to the general shape of the diurnal distribution, especially as to secondary maxima. Very little is known about the distribution of the echoes with latitude.

CHAPTER II

EQUIPMENT AND EXPERIMENTAL OPERATION

2.1 Equipment Location

The experiment described in this report utilized two chains of auroral radars located in the United States; they were the U.S. contribution in the field of radar aurora to the worldwide studies of aurora and airglow made during the International Geophysical Year. These two chains comprised a relatively close-spaced series of stations in a magnetic north-south line spanning the auroral zone and a relatively widespread series of stations in a magnetic east-west line located south of the auroral zone. Thus studies of both the latitudinal and longitudinal behavior of the radar aurora could be made. In this report only the latitudinal effects will be studied; therefore only the magnetic north-south chain will be considered.

The north-south chain was located completely within Alaska and consisted of five stations running from the Arctic Ocean on the north to the Aleutian Islands on the south (Figure 1). Because of the large distances between towns in Alaska and the shortage of transportation in the more remote areas, the north-south line is somewhat distorted. The stations of the most interest are those that span the auroral zone, and these are in a fairly straight line (i.e. College, Farewell, and King Salmon). The northermost station, Barrow, is displaced to the west about 15 degrees in geomagnetic

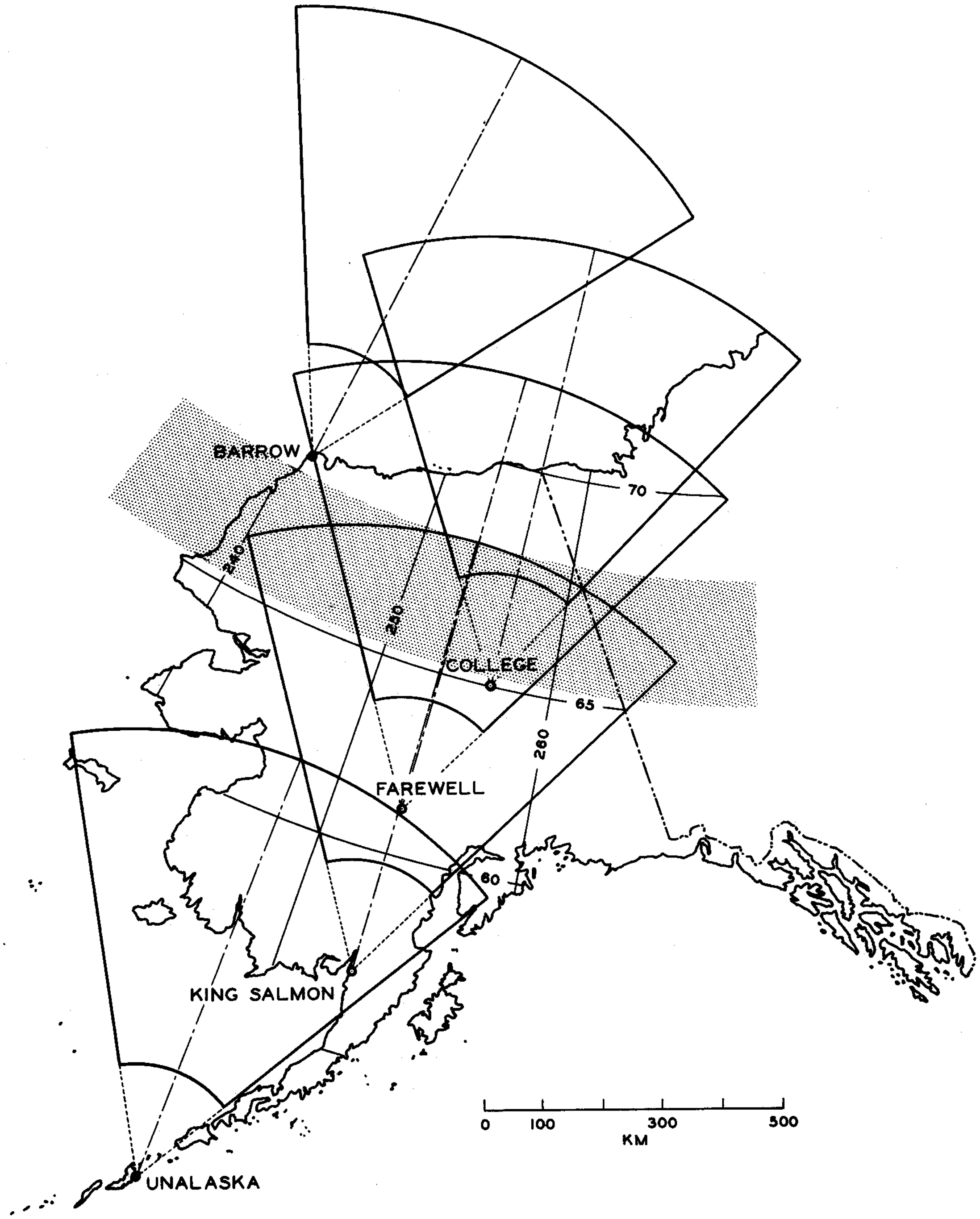

Fig. 1. Map of Alaska showing station locations and antenna fields of view.

longitude, and the southermost station, Unalaska, is displaced west about 10 degrees. Data will be used from the Barrow station and comments will be made on its displacement in longitude. The Unalaska station will not be used because aurora was recorded there only once, briefly, during the entire period of operation despite the common indication of meteors on the records, showing that the equipment was working properly.

The map in Figure 1 also gives an indication of the field-of-view of each radar. The radars were operated with fixed antennas directed in the magnetic meridian. They consisted of two, four-element, horizontally polarized, Yagi antennas (Uda and Mushiake, 1954) stacked vertically and located one and two wavelengths above the ground (Figure 2). These antennas were described as having a horizontal beamwidth (to the first minima) of about 60 degrees which determined the sides of the coverage pattern on the map, Figure 1. The effective coverage was somewhat narrower than this; the half-power beamwidth was about 40 degrees. The far range cutoff was due to the screening effect of the earth and occurred at about 1200 kilometers range for E layer heights. The close range cutoff occurred at about 300 kilometers, and was possibly caused by the increase of the off-perpendicular angle which occurred quite rapidly as the range decreased below 300 kilometers. It is worth noting here that both sides of the visual auroral zone as well as the zone itself was probed by at least two radars.

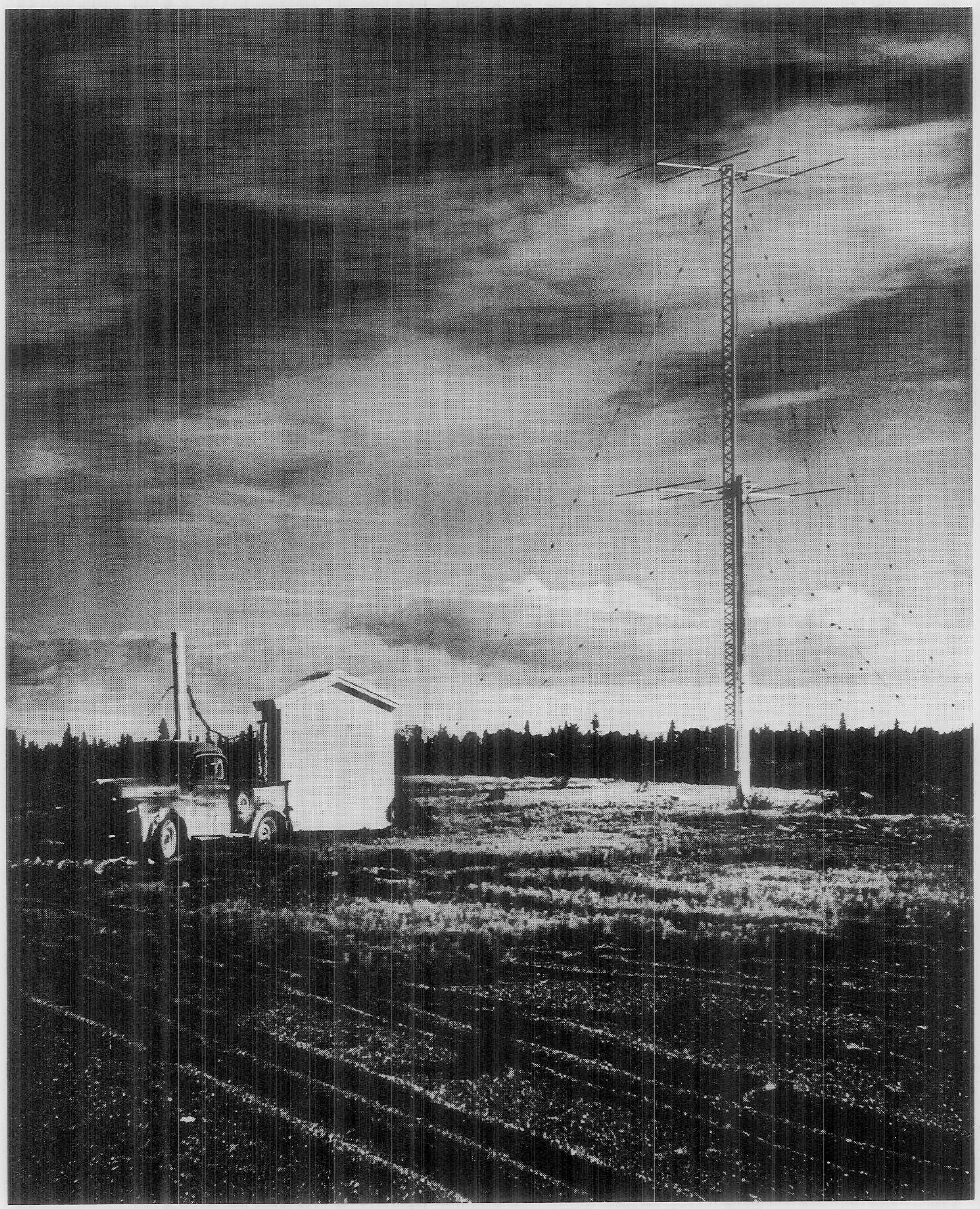

Fig. 2. King Salmon station and antenna.

The radars were installed and tested carefully to assure that their operating conditions were nearly identical. The identical units were made by the same firm in one production run.* The transmitter power and receiver sensitivity were adjusted daily to standard operating conditions and the corrections necessary to bring the equipments back to standard conditions were recorded.

2.2 Radar Equipment

The radar consists of the following sub-units: a pulsed, crystal controlled transmitter; a stable, low noise, crystal controled receiver; a transmit-receive switch to couple the receiver to the antenna; a time base generator; an oscilloscope; a camera drive unit; and the necessary power supplies. A block diagram is shown in Figure 3, and a photograph of the production units is shown in Figure 4.

The transmitter follows closely the design of a conventional VHF communication transmitter. It has a well shielded crystal oscillator, followed by a gated buffer amplifier which is controlled by keying pulses from the time base generator. Following the buffer amplifier are two class-C doubler amplifiers and a class-C final amplifier. All stages following the gated amplifier have special provisions to keep the operating potentials constant during the pulse as well as during the interval between pulses.

*Levinthal Electronic Products Inc.

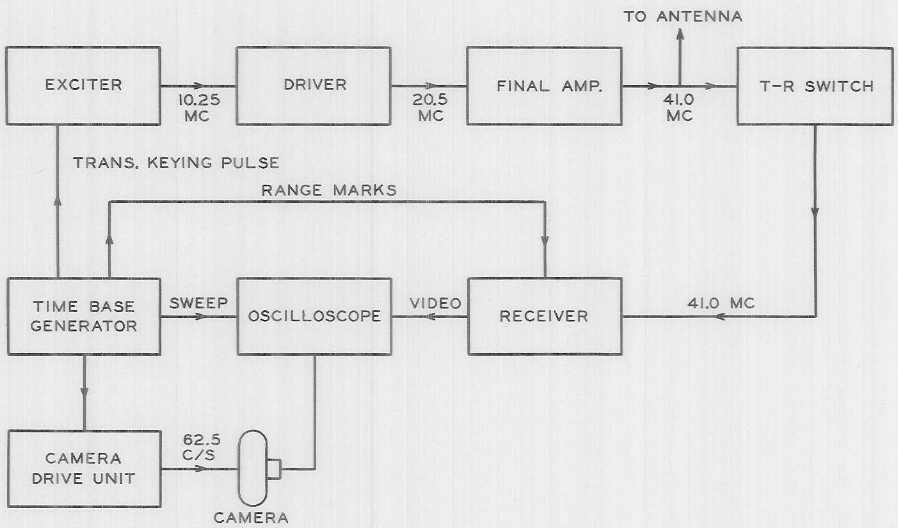

Fig. 3. Block diagram of the auroral radar.

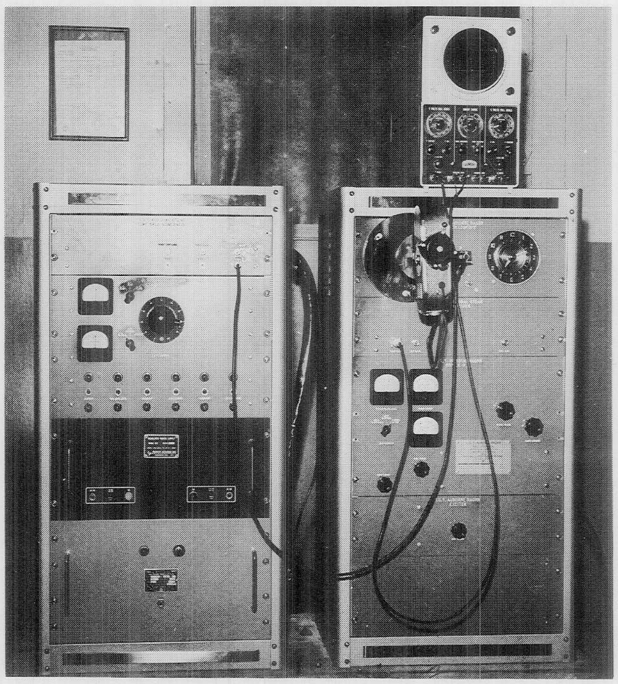

Fig. 4. Radar system in operation.

The receiver is a double-conversion superheterodyne with two crystal controlled local oscillators. A single-stage, dc-coupled, video amplifier is included in the receiver with a video signal clipping circuit to prevent blooming of the intensity modulated oscilloscope display.

The transmit-receive switch consists of a pair of lumped-constant quarter-wave transformers, with a characteristic impedance of 1000 ohms, placed back-to-back. A type 1B32/532A gas diode is placed between these two transformers. During reception, the two transformers acting together produce no impedance transforming effect, and the 50 ohm receiver is connected to the 50 ohm antenna feed line. During the transmission period the gas diode conducts, producing nearly a short circuit between the two quarter-wave transformers. This very low impedance, when transformed by one quarter-wave transformer appears as an extremely high impedance in parallel with the 50 ohm antenna feed line, effectively disconnecting the receiver from the antenna feed line. In practice, it is possible to realize more than 35 db of loss during transmission, with an insertion loss of 1 db. An anti-TR switch was not used because the transmitter impedance during standby was large compared to 50 ohms, so that almost all of the echo power was delivered to the receiver.

The time base generator is the control center of the entire radar. It consists of a 750-cps tuning-fork controlled oscillator, a binary frequency dividing chain, a pulse generator, and a sweep generator. The 750-cps signal produces the 200 km range marks directly; it is then divided by 8 to produce the transmitter keying frequency and saw-tooth sweep-triggering frequency. A pulse generator produces the transmitter pulse and an identical pulse of opposite polarity to blank the oscilloscope during the transmit period.

In addition, 187.5-cps square waves, derived from the divider chain, are supplied to the camera drive unit to provide a stable frequency to drive the camera motor.

The oscilloscope is intensity modulated by the video signal which is dc-coupled from the video amplifier to the grid of the cathode ray tube. Two sweep plates are connected together to prevent any vertical deflection, and the others are connected to the sweep generator in the time base generator. A special 16-mm camera which has no shutter and drives the film through the focal plane continuously is employed to photograph the intensity modulated oscilloscope.

The camera drive unit divides the 187.5-cps square waves to 62.5-cps. This waveform is then amplified and used to drive the camera motor which provides a constant film rate of 50 frames per hour independent of power line frequency. In addition, a special clock, whose operation is independent of both the power line frequency and the camera drive unit, puts marks on the edge of the film every hour. In case of failure of this marking system the timing accuracy is $\pm$ 2 minutes, and with the clock the hour marks are within $\pm$ 15 seconds.

Each day, when the operation parameters were adjusted to standard conditions, an identification was photographed onto the data film. This identification consisted of three rows of four digits each; a typical example is:

0123
C750
0005

The first two digits in the top row are the month, and the second pair, the date. The first digit in the second row is a station code, according to the following plan:

B - Barrow, Alaska
C - College, Alaska
D - Rapid City, S. Dak.
F - Farewell, Alaska
K - Kotzebue, Alaska
M - Macquarie Island
N - Ithaca, New York
P - Pullman, Washington
S - King Salmon, Alaska
U - Unalaska, Alaska

The second digit in the second row is the year, 7 for 1957 and 8 for 1958. The last two digits in the second row are the tens of volts of RF at the output of the final amplifier. The four digits in the third row give the Universal Time when the camera was removed from operation. The example above would be January 23, 1957, College, Alaska, final amplifier output voltage = 500 volts, camera removed from operation at 0005 U.T. This daily identification provides the most frequently needed information for the analysis of the data, making it unnecessary to refer often to the more detailed daily operations log. A sample film is shown in Figure 5.

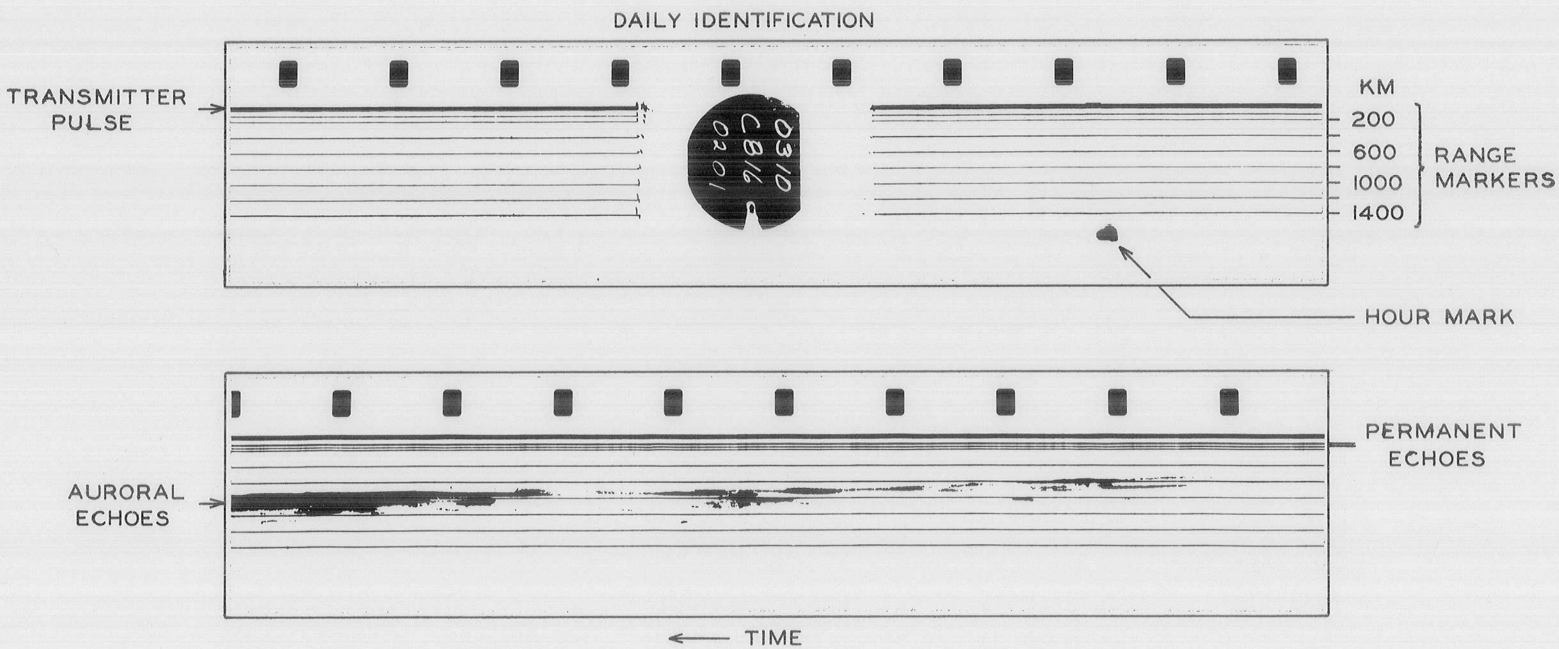

Fig. 5. Sample of typical film strip.

The gain settings of the receiving system are adjusted so that the range of signal strength between a minimum threshold signal and a signal which will produce the maximum intensity is small; this results in an appreciable darkening of the film for echoes just above the threshold. The mimimum signal threshold is checked daily and corrected if necessary to a value of 0.6 microvolt at the 50 ohm input. The transmitter output power is calculated by measuring the RF voltage at the final amplifier output (antenna feed line input) and using the known impedance of the antenna. This voltage is measured daily and corrected to be 500 volts across the 50 ohm antenna feed line. In addition to these fundamental operating parameters, the voltages and currents of many of the circuits are measured and logged daily. The important operating characteristics are summarized in Table I.

TABLE I

Output power	5×10^3 watts
Receiver threshold	7×10^{-15} watts
Pulse duration	100 microseconds
Receiver bandwidth	10^4 cycles/second
Pulse repetition rate	93.75 pulses/second
Antenna gain (one way)	12 db (approx.)
Range displayed	1600 kilometers

The operating frequency was slightly different at each station to avoid interference between stations. Actual frequencies are listed in Table II.

TABLE II

Barrow	40.94 Mc/s
College	41.00 Mc/s
Farewell	40.88 Mc/s
King Salmon	40.94 Mc/s
Unalaska	41.00 Mc/s

2.3 Antenna System

The horizontal polar diagram of the antenna has a width of about 60 degrees between the first minima. The effect of side lobes has been discussed by Gartlein et al (1960) who calculated the effect of a lobe located about 60 degrees from the center of the main lobe and having an amplitude of about 1/8 of the main lobe, presumably in power. One must consider the contribution of this side lobe to the data obtained from the main lobe. If a thin, uniform auroral arc aligned parallel to the magnetic longitude lines is located 700 km away at the point of closest approach, the side lobe would intersect it at a range of about 1000 km. Assuming the returned power from an auroral scatterer is proportional to $G^2 R^{-n}$ and for the moment taking $n = 2$, as would be appropriate for a uniformily illuminated surface scatterer, one can compute the ratio between the power from the main lobe and that from the side lobe as being 1:0.0078, that is, a contribution of less than 1% from the side lobe. The contribution will be even less if $2<n\leq 4$. The display system is voltage sensitive, however, so one must take the square root of this number

giving 1:0.088 or a contribution of about 10% from the side lobe, again an upper limit.

The foregoing discussion does not consider another important factor in determining the strength of the auroral echoes, the aspect sensitivity. In all the Alaskan stations except King Salmon, the aspect angle becomes less favorable as the echoing centers move off the meridian plane which would tend to reduce still further the contribution from the side lobe. At certain ranges for both the stations at King Salmon and Cornell University the aspect angle becomes more favorable when the echoing center moves a short distance off the meridian plane; however, at King Salmon by moving the required distance of 60 degrees from the meridian plane to utilize the side lobe, the aspect angle again is found to be unfavorable. One may conclude, therefore, that the side lobe contribution is negligible in the Alaskan data and that virtually all the echoes recorded are arriving through the main lobe of the antenna.

The vertical polar diagram of the antennas is of considerable interest since it will modify the form of the distribution of echo occurrence with range, caused by the different angles of arrival of echoes coming from different ranges. In order to check the theoretical value which will depend on the assumed properties of the ground, a measurement was made by means of a captive balloon carrying a small battery powered target transmitter which was raised and lowered in front of the antenna. This operation was carried out as far away from the antennas as possible to avoid near-field effects; the closest measurement was made at about 30 wavelengths. As the balloon was raised and lowered, the angular displacement at the antenna was measured with a surveyor's transit. By taking readings during ascent and descent any drifts in the target transmitter output could be corrected.

Two measurements were taken, one in the fall before any freezing weather, and the other during the winter. Both measurements are shown in Figure 6 along with the calculated value. The abcissa is given in units of range rather than angle; this unconventional presentation is utilized to aid in visualizing the effects on the plots of echo distributions vs range given in Chapter III. The conversion from elevation angle to range is calculated by assuming a height for the echoing region of 110 km (Unwin,1959) and no refraction; the effect of introducing refraction would be to shift the range origin to the left. However, refraction must be very small because the echo distributions show a virtual cutoff at 1200 km, the earth shielding range.

2.4 Echoing Geometry

An important parameter in the interpretation of the radar auroral echoes is the angle between the ray from the radar and the earth's magnetic field at the point where the echoes originate. Unfortunately it was not possible to measure this angle directly; in fact the only information that is available

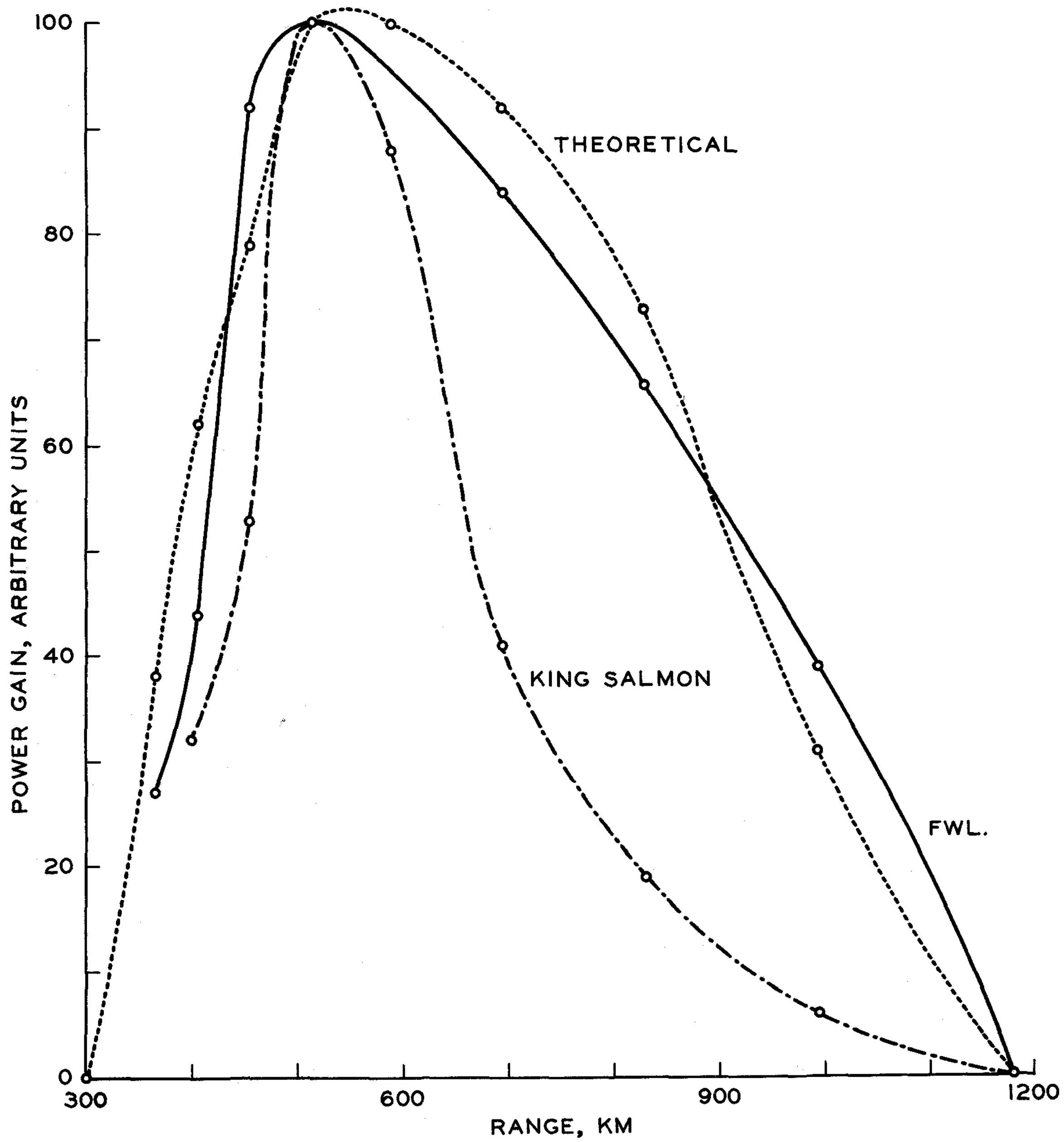

Fig. 6. Antenna gain.

applies to the field about 100 km away from the echoing region. The direction of the field is fairly well known on the earth's surface based on interpolation between measurements made in magnetic surveys. A good estimate can be made of the field direction at about 200 km height by determining the direction of auroral rays (Harang, 1951). Since the data are not available to make determinations by the second method except at selected sites and at special times when a corona is present in the magnetic zenith, the only method left is to utilize the surface data and attempt to extrapolate it up to the height of the echoing region.

The method used is illustrated in Figure 7. The surface value of the dip angle, I, was read from the Isoclinic Map of Alaska, 1955.0, No. 3069i, published by the U.S. Coast and Geodetic Survey. The field of the centered dipole was fitted to this surface direction, and this field line was then followed up to a 110 km height, where the angle between the field line and a line from the radar was calculated. For the desired accuracy of these calculations, 0.2 degree, the field lines are straight over this 110 km interval; therefore, the calculation can be simplified by using $I_a = I$. It should be noted that the "propagation angle" as used in this report is the angle between the field line and the line from the radar measured clockwise in Figure 7; this angle is greater than or equal to 90 degrees for all the Alaskan stations except King Salmon. Figure 8 shows the propagation angle as a

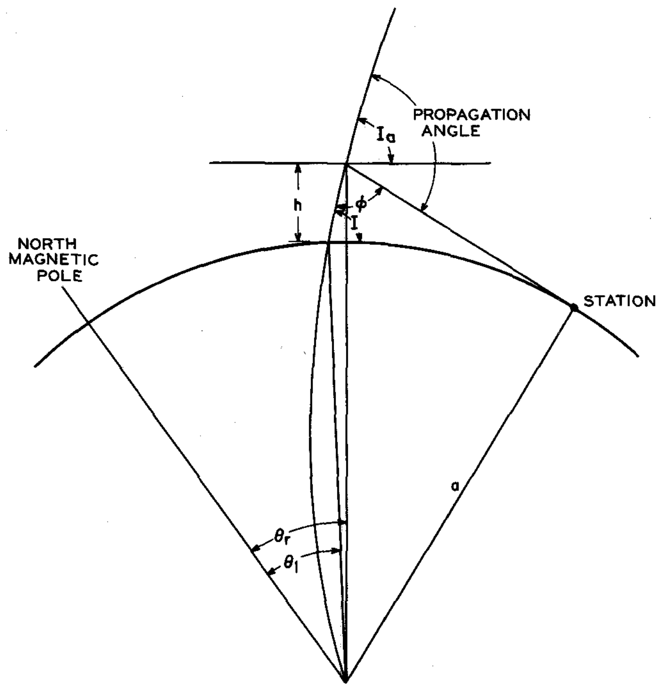

Fig. 7. Geometry of auroral reflection.

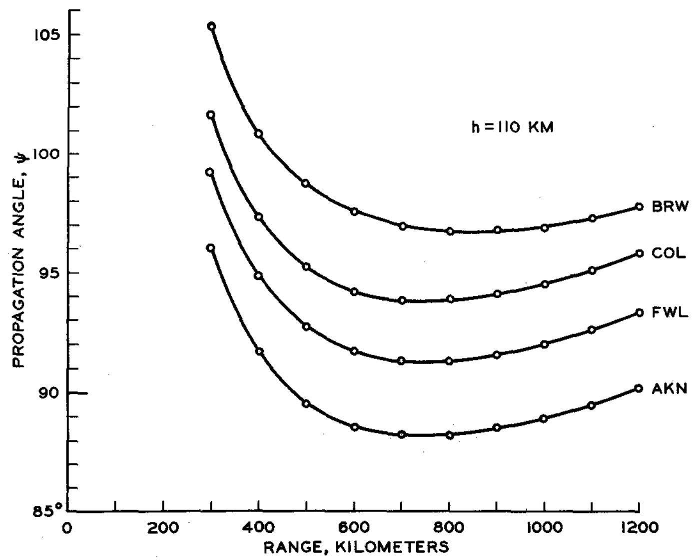

Fig. 8. Propagation angles.

function of range for the four Alaskan stations.

It must be emphasized that the angles shown in Figure 8 are approximations and apply only near the magnetic meridian. The propagation angle at any range will increase as the echoing region moves either east or west from the magnetic meridian.

These propagation angles, while they are useful in interpreting the radar returns, are not necessarily the actual angles that are encountered at the aurora. The line between the radar and the aurora may not be exactly a straight line due to refraction in lower ionospheric layers; however, this effect is small as an effective cutoff in echoing activity occurs at a 1200 km range, which is the earth's shielding range for no refraction, at 100 km height.

The largest source of error is probably caused by the fact that the field lines do not follow exactly the dipole approximation. The field lines are even known to change their orientation during a magnetic disturbance. Harang (1951) reproduces some original work of Störmer (1938) describing an analysis of the movements of the radiant point of coronal forms. This point was traced through a movement of as much as four degrees in inclination during the course of the great auroral display of 22-23 March 1920. The auroral rays forming the corona are aligned with the magnetic field, and their motion reflects a similar distortion of the local magnetic field, probably at 200 to 300 km heights. As the disturbance-current systems are usually considered to flow in the E layer, one would expect any field distortions to be as great or greater than those occurring higher up; if this is the case these distortions could exert a controlling effect on the echo geometry since the angular distortions could easily be as large as the off-perpendicular angles determined from the mean field and given in Figure 8.

When similar calculations of propagation angle at King Salmon are made for a height of 100 km, the range for a 90° propagation angle shifts 80 kilometers closer to the station. By comparing the propagation angle curves for the two heights with the measured echo distributions shown in chapter III, Figure 13, it is seen that the curve for the 110 km height fits much better. Since the 110 km height has been carefully measured elsewhere (Unwin,1959), this agreement can be taken as indirect support for the method of calculating propagation angles.

2.5 Scaling of the Films

The recording cameras drove the film through the camera at a rate of 50 frames per hour. At this rate a 100 foot roll of film was used every three days; the total film taken during the year 1958 amounted to about 50,000 feet, creating a major scaling problem.

The nature of the range-time presentation makes it necessary to examine all of the film rather than using a frame-by-frame procedure thus neglecting the spaces between the frames. In addition, the time reference marks occur only once each hour, i.e. every 50 frames or approximately every 15 inches. This means that one must view at least 15 inches at one time or provide some alternate means of carrying the time reference throughout each hour. In order to study the distributions of the auroral echoes it was decided to break the time scale into one hour intervals and the range scale into 100 km wide zones and then scale the portion of time that aurora was present in each of these subdivisions.

Unfortunately, the film contains more features than just auroral echoes; any interference will darken the film, as will light leaks, echoes from phenomena other than aurora, chemical fogging in processing, and a host of other extraneous sources. It is therefore difficult, if not impossible, to scale this film by means of an automatic device relying on photocells to read the film. A semi-automatic machine is certainly indicated to facilitate the scaling operation - that is, a machine in which as many of the operations are made automatic as possible, but one in which the final choice is made by a trained operator viewing the film directly.

Such a machine was designed and built. A block diagram is shown in Figure 9. It makes use of a Remington-Rand electric film viewer in which the film is transported past the viewing screen by an electric motor. A photocell monitors the edge of the film and with the aid of an amplifier and a relay, provides a pulse for every sprocket hole in the edge

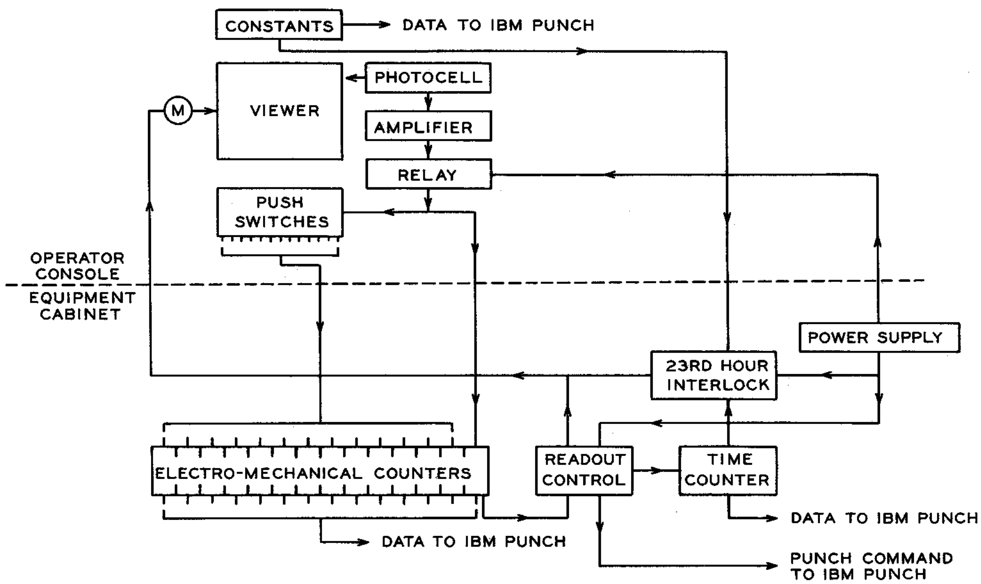

Fig. 9. Block diagram of the scaling machine.

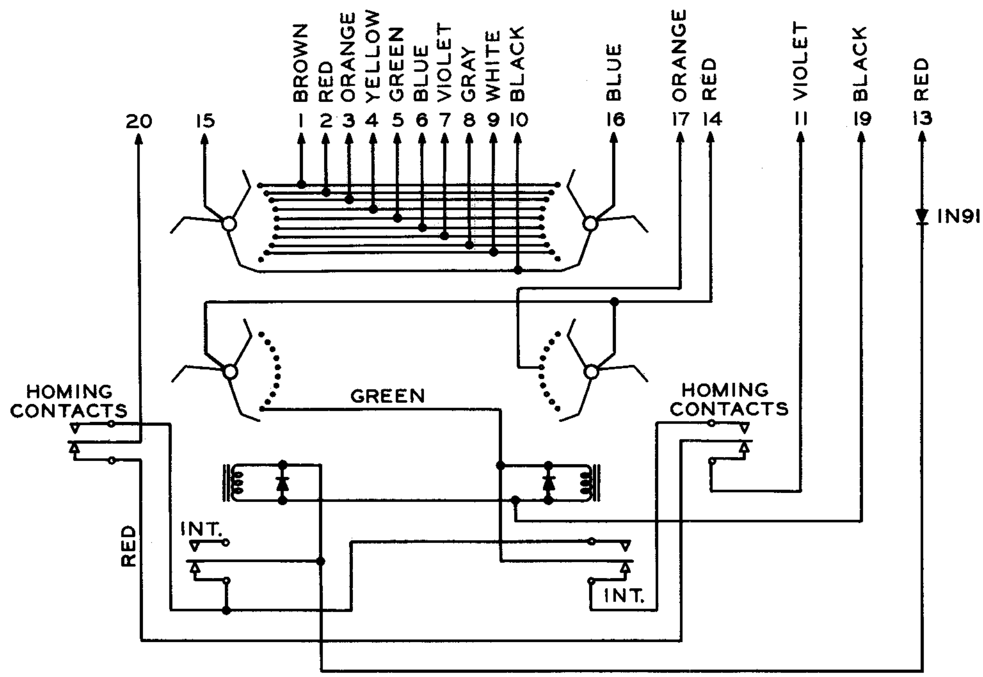

Fig. 10. Circuit diagram of a Standard Counter.

of the film. These pulses are referred to as "frame pulses" below. Since there is one sprocket hole for each frame, 50 of these frame pulses correspond to one hour of film. By initially setting this system to the hour marks on the film at the beginning of each day, the timing is established for that day's scalings.

A keyboard of 13 push-switches was installed in the machine with one key for each 100 km range zone on the film. The frame pulses were routed through these key switches to electro-mechanical counters (Figures 10 & 11) which accumulated a count representing the number of frames that the key had been held down. Thus by simply holding the appropriate key down when there was aurora present in that range interval, the operator sums the amount of aurora occurring during that hour.

The frame pulses were directly connected to an electro-mechanical counter arranged to indicate when its total had reached 50, or one hour of film. The total-of-50 information was routed to a readout control panel which stopped the film transport and commanded a readout cycle. During this cycle the totals in all the counters were punched into an IBM card along with the constant information of station, year, month, and date. At the end of the readout cycle the machine reset all counters except the hour counter to zero, advanced the hour counter, and waited the operator's command to resume the film motion. The output of this system is one IBM card per

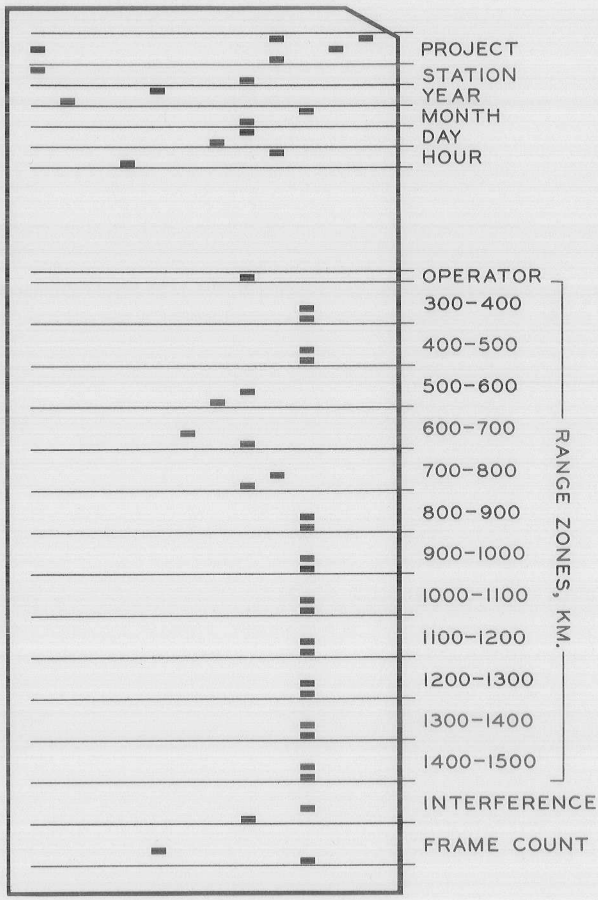

Fig. 12. IBM card layout.

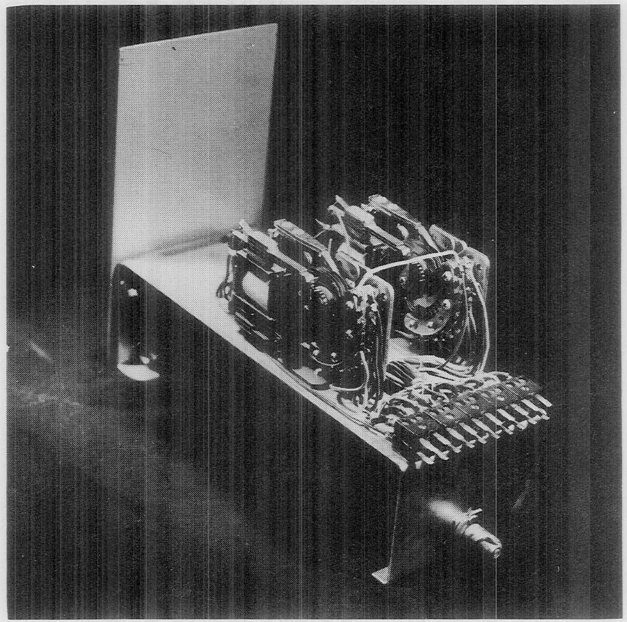

Fig. 11. Standard Counter Unit.

hour of film data. This card identifies itself and contains the number of one-fiftieths of an hour that echoes were present in each 100 km range zone; also it contains a count of the number of frames contributing to that hour. These cards are shown diagrammatically in Figure 12.

The two columns that have not been mentioned are the project and operator columns. The project code was used to avoid any mixup in cards; the initial scalings are coded AR1. Cards used in subsequent calculations are AR2, AR3, etc. The operator code was utilized to separate the scalings of different operators when duplicate scalings were being compared for a check on scaling accuracy.

Several months of data films were scaled twice by different operators, and some months were done a second time by the same operator after a time lapse of several months to determine variations between different operators and to determine how close an operator could reproduce her own work. The variations between the duplicate scalings can be attributed to two principal sources: 1) The range axis on the film is divided by "range-marks" spaced in 200 km intervals, and it was necessary for the operator to visually divide each zone in half; echoes lying very close to this imaginary dividing line could be assigned to the wrong range zone, 2) Echoes occasionally have a very slow build-up and decay in amplitude, giving rise to some uncertainty as to the exact time when they begin and end. The radar equipment was designed to avoid this trouble as much as possible by providing a rapid increase of intensity on the recording oscilloscope with signal increase above the minimum threshold, but inevitably some echoes will fall just above the threshold, causing this uncertainty.

By means of these "check" scalings it was determined that one operator was able to reproduce her own scalings with an average error of about 2%. The error between different operators was somewhat larger, averaging about 6% and showing a fairly consistent bias, that is, one operator would consistently detect the weak echoes whereas another would not. This consistent error was about 3%.

Another major source of error enters at this stage, namely the confusion of other echoes with auroral echoes during the scaling process. Two major sources of echoes appear on the records other than aurora; the first are backscatter echoes propagated via the F layers of the normal ionosphere.

The F echoes come in through the back lobe of the antenna from the south when the F layer critical frequency becomes high enough to support 41 Mc/s oblique propagation at the path midpoint. This condition only exists during the middle of the day in the winter months and can usually be recognized by its symmetrical occurrence about noon and by its symmetrical changes in range which are also centered about noon. Because the entire interpulse period is displayed on the oscilloscope which is photographed, a range ambiguity of

1600 km is introduced; these F layer echoes will first appear at around 3700 km, that is, on the third fold of the trace. As the electron density increases at the path midpoint, this echo moves into the second fold, with a range less than 3200 km, and then moves back out again after noon. Because of the large scattering area contributing to this echo, it often appears widely spread in range, and with its appearance on both the second and third fold of the sweep it often appears to cover almost all of the 1600 km. These characteristics usually make its identification obvious and it is left out in the scaling; nevertheless, when it is mixed in with auroral echoes or when it has features that tend to mask its identity, it may be scaled as an auroral echo. Undoubtedly some contamination from this source is present in the distributions for the winter months during the middle of the day. The error from this incorrect identification is estimated to be less than three percent.

The second source of contamination is caused by meteor echoes of long duration. Fortunately these echoes are quite rare, especially those lasting for more than 2 frames; their total contribution to the distributions is less than one percent.

*

CHAPTER III

DISTRIBUTION OF AURORAL DISTURBANCES

3.1 Manipulation of Raw Data

The period covered by this report is the calendar year 1958, the last full year of the International Geophysical Year. Some noncontinuous data available from the first 6 months of the IGY are not included in this work. These first data do not represent uniform operating conditions since the initial performance tests of each equipment and the training of the operators took place during this time. The station at Unalaska operated only for the last six months of the IGY because a skilled operator was unavailable. The King Salmon station operated at very reduced transmitter power until mid-1958. Data included here are for the period after June, 1958, when the transmitter power was at the standard operating value. The balance of the stations operated continuously except for an occasional short duration equipment failure. All the data have been normalized to the number of hours of operation and are expressed as the per cent of operating time that echoes were present.

The output of the data-film scaling operation was IBM cards where one card represented an hour of film from each station. These cards contained identifying information: station; date; time; and the number of one-fiftieths of an hour, referred to below as "intervals", that echoes were present in each 100 km range zone starting with the 300 to 400 km zone and going out to the 1400 to 1500 km zone. The cards also included the number of intervals that interference was present to such a degree that the scalings were doubtful. In addition, the number of intervals that were viewed to produce that particular card were included in the information, thus enabling one to correct for incomplete hours caused by daily checks, failures, etc.

The principal manipulation of these cards was to sort them into groups consisting of all the cards for a month from each station for each hour of the day. These groups were then processed by the Electric Accounting Machine (IBM 402) which summed the number of intervals during the month that echoes were present in each range zone for each hour. It also summed the number of intervals that were scaled to produce these cards. The totals thus produced were then reduced to per cent occurrence by dividing the echo totals by the scaled intervals totals; this operation was done in a Calculating Punch (IBM 602). Other intermediate totals were formed to check for errors in the computations, a necessary step when using the computing machines.

At this point, the properties of the echo recording system and the assumptions necessary to interpret the percentages determined above as representing the relative occurrence of aurora should be considered. The receiver was operated at relatively high gain, and the intensity-modulated recording oscilloscope was adjusted to have a suppressed threshold.

The receiver gain was adjusted to give a barely detectable response with an input of 0.6 microvolt across a 50 ohm resistance, or with an input of 7×10^{-15} watt. The result of this high-receiver-gain suppressed-threshold adjustment was that an echo which barely exceeded 0.6 microvolt would give a strong indication, while one of only slightly less than 0.6 microvolt would give no indication. The value of 7×10^{-15} watt was chosen for this threshold to exclude background fogging of the film caused by galactic noise. On the other extreme, a clipping circuit was placed in the video output of the receiver to prevent blooming on the oscilloscope and over-exposing the film on extremely strong echoes. The action of this circuit resulted in essentially a step function response of the recording system to echo amplitude.

A short program of measuring the echo amplitudes was conducted for the purpose of determining the amplitude of the strongest echoes (Leonard,1958); a side product of this work was the conclusion that the echoes do not have any preferred amplitudes in the range detectable by this equipment. The strongest echo had an intensity of 2.7×10^{-11} watt and the weakest echoes were just barely detectable in the noise level of about 5×10^{-15} watt. Therefore the assumption made here was that if the threshold was changed it would not affect the shape of the distributions but only the magnitude.

3.2 Distribution of Echoes in Range and Latitude

3.2.1 Distribution at each station - The shape of the curves representing the distribution of echoes in range can be roughly predicted by considering the scattering mechanism. If the echoes originate from a small scatterer the simple radar equation (1) will hold and the curves will represent the distribution of the ionospheric disturbances modulated by the dependence on the inverse distance and the gain of the antenna. If on the other hand, the scattering area, σ, is dependent on the propagation angle as postulated by Booker (1956), another influence will be seen on curves and they will tend to peak at the minimum value of $\left|\psi\text{-}90\right|$.

The echo distributions shown in Figure 13 are the average distributions as a function of range for each station. The ordinate in all cases is the percentage of time that echoes are present for the entire year; note the change of scale on the vertical axes. On the same range axis the propagation angle, ψ, is replotted for each station from Figure 8 in Chapter II.

Two features can be noted immediately, the most striking is that the curves all peak at the minimum value of the off-perpendicular angle $\left|\psi\text{-}90\right|$. The other feature is that the curves show a decrease for the higher ranges as would be expected from the inverse distance dependence of the radar sensitivity. Both of these effects are most noticeable in the curves from King Salmon, the most southerly station. At this

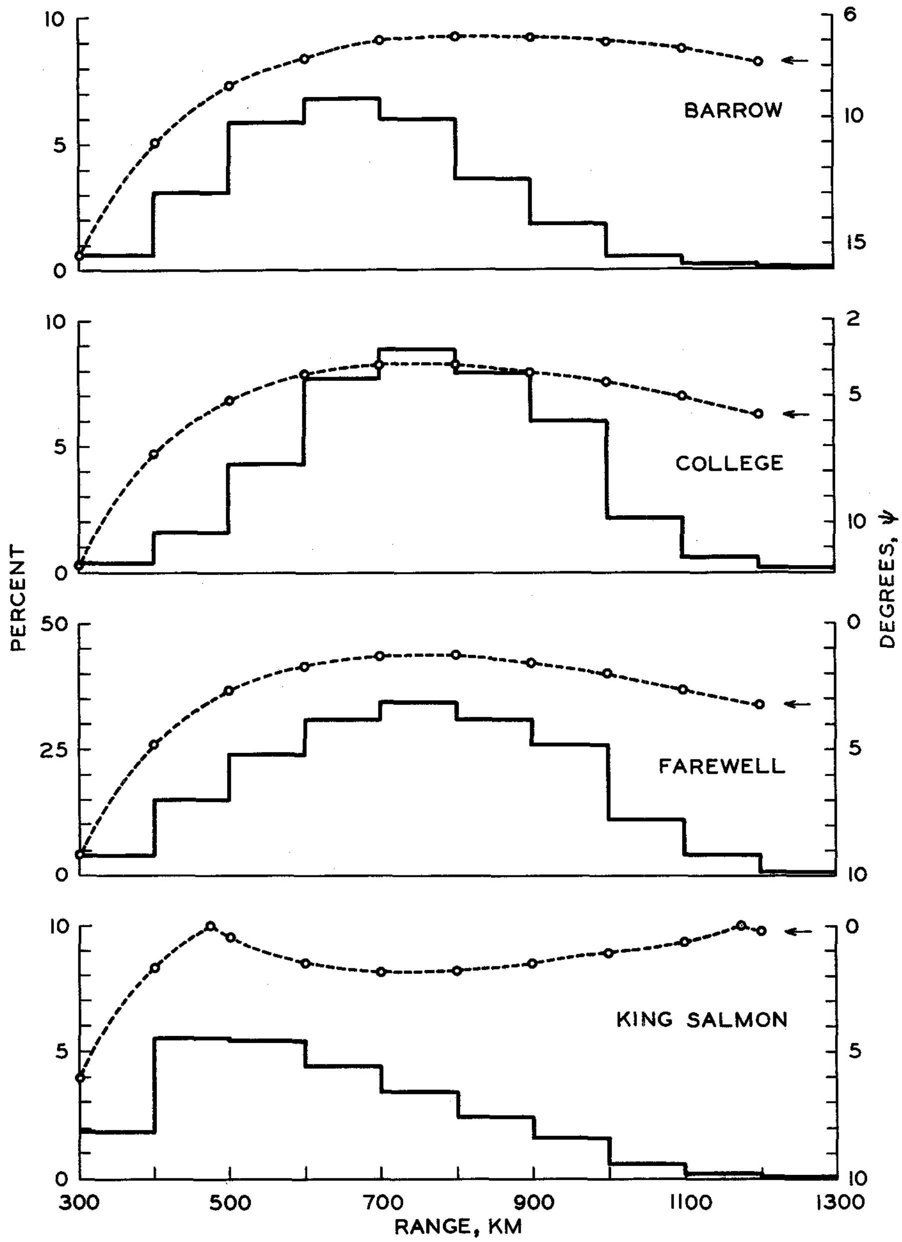

Fig. 13. Occurrence of echoes as a function of range.

station, the ray from the radar is exactly perpendicular to the field lines at a range of 470 km; beyond this range, the propagation angle decreases to 88 degrees at 700 km and then increases back to 90 degrees at the outer limiting range of 1200 km. Few echoes are seen at this extreme range because of the large loss of sensitivity from both the range extinction and the low antenna gain at low elevation angles.

There are small departures from these annual curves when the data is summed over one month only. These departures show no systematic behavior other than the degree of overall disturbance for each month. That is, the height of the curves may change appreciably but the general shape does not. A representative sample of this condition is shown in Table III which lists the data from College for the year by months as well as the annual average used in plotting the College curve in Figure 13.

TABLE III

Percentage Occurrence of Echoes for College, 1958

	Range km									
Month	300	400	500	600	700	800	900	1000	1100	1200
Jan.	0.5	1.4	6.1	12.2	15.1	15.2	12.5	5.8	3.0	0.4
Feb.	0.4	0.8	3.5	7.9	10.9	10.4	8.3	2.9	0.5	
Mar.	1.0	1.3	4.6	9.0	10.2	9.1	6.3	1.8	0.3	
April	1.0	2.8	7.8	13.7	14.8	13.3	10.2	2.6	0.3	0.1
May	0.4	3.9	7.5	10.4	10.1	8.3	6.5	1.3	0.2	0.1
June	0.4	2.2	4.7	7.2	7.2	5.9	4.0	1.0	0.3	0.2
July	0.2	0.8	0.6	4.4	8.1	7.9	6.5	4.8	1.6	0.5
Aug.	0.3	0.9	2.4	3.8	4.0	3.3	2.6	0.3		
Sept.	0.1	0.7	1.8	3.1	4.2	3.7	2.8	0.4		
Oct.	0.2	0.9	3.2	5.6	5.9	5.0	4.2	0.9	0.1	
Nov.	0.1	1.1	4.2	6.1	5.8	4.0	2.5	0.4	0.1	
Dec.	0.6	2.1	5.1	8.8	9.0	7.4	5.5	2.4	1.0	0.8
Annual Avg.	0.4	1.6	4.3	7.7	8.8	7.9	6.0	2.1	0.6	0.2

From this table it is apparent that the months of August, September, October, and November were low activity months, a condition also noted in other measurements of ionospheric disturbances.

3.2.2 Construction of a radar auroral zone - When any one of these distributions is viewed by itself, it is tempting to regard the curve as representing the "auroral zone"; especially if the radar is known to be probing the ionosphere near the auroral zone as determined by other measurements. When all four are examined simultaneously, one sees four different, mutually exclusive "auroral zones", one for each radar. If these distributions are replotted on separate range axes that are referenced to the geomagnetic latitude of the station, one obtains the curves of Figure 14. The echo distribution curves which should be histograms are drawn as smooth curves.

It is extremely tempting to conclude that the radar observations indicate a "radio auroral zone" especially when this auroral zone is in such good agreement with the visual auroral zone determined by others (Vestine, 1944; Elvey et al, 1955; Davis and Kimball, 1960). In Figure 14, the visual auroral zone is determined by Davis and Kimball (1960) from an anlysis of All-Sky Camera films taken in Alaska during the IGY. It would be convenient indeed, if one could turn to theory at this point and correct these distributions for aspect angle, range dependence, antenna gain, and all other

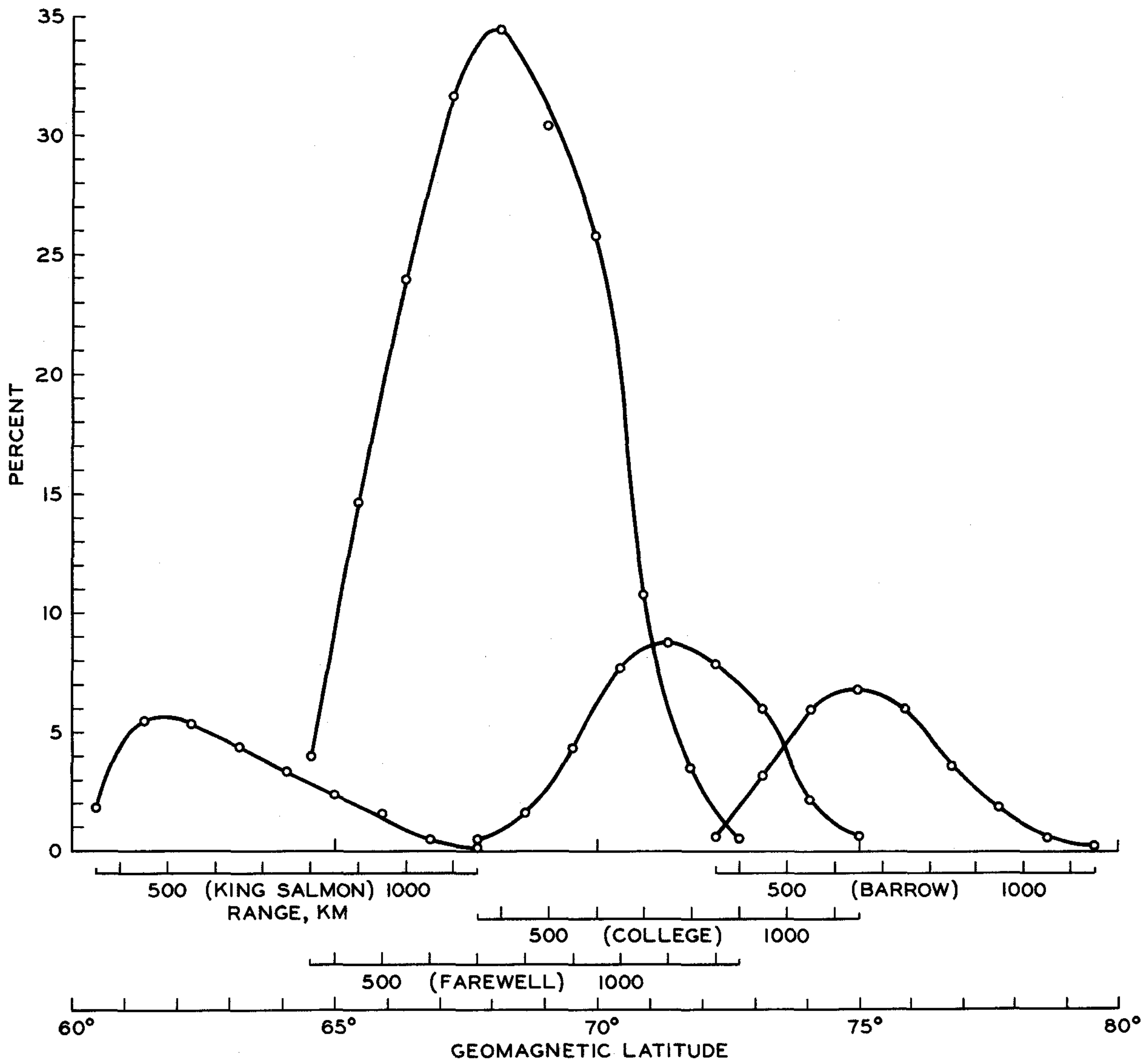

Fig. 14. Radar auroral zone.

experimental parameters to produce a single curve representing the distribution of ionospheric disturbances only. Unfortunately at this time no adequate theory exists by means of which this can be done. Attempts to fit the overlaps between two radar observations by any of the present theories fail.

In view of the possibility that the magnetic field deviates appreciably from its mean orientation (Harang, 1951), it seemed desirable to investigate if such deviations, when coupled with the Booker scattering theory (Booker, 1956), could supply the necessary corrections to the curves in Figure 14. As a first approximation, it was assumed that the duration, t, of any off-perpendicular angle, ψ, was given by

$$t = \exp\left[-\frac{1}{2}\left(\frac{\psi-\psi_0}{\sigma}\right)^2\right] \qquad (2)$$

where ψ_0 is the off-perpendicular angle as determined from the mean field. By using this relation and assuming that the scattering columns were longer to give a sharper scattering polar diagram, it was possible to fit roughly one overlap, King Salmon-Farewell, by adjusting the values of the two constants σ and L (the column length). Using these values of the constants for the next overlap, Farewell-College, the fit was much poorer. In applying them to the last overlap, College-Barrow, the fit was extremely bad. New values of the constants could be found to improve the fit at any overlap but this just resulted in degrading other overlaps. For comparison, another test was made using

$$t = m(\psi - \psi_o) + b \tag{3}$$

which showed the same effect.

A second result of this method was that the auroral zone was displaced to the north from the position of the visual auroral zone. In fact, it was apparently beyond the farthest range detectable of this experiment, 80 degrees geomagnetic latitude! The failure of this method of analysis can arise from two principal sources; either the models of the distortions that were assumed may be very misleading, or the ionospheric disturbances responsible for the auroral echoes may be different from one station to the next. In any case, the assumptions are too extensive and too numerous to make this type of approach fruitful.

It is clear that the propagation angle plays a significant part in the sensitivity of the radar. By choosing a range zone from each radar that has a certain propagation angle, one is able to draw some specific conclusions regarding the distribution of ionospheric disturbances. The most obvious zone for such a comparison is the 400 to 500 km zone at King Salmon; it is in this zone that the radar ray achieves exact perpendicularity with the mean field lines. A similar zone is the 700 to 800 km zone from Farewell which misses perpendicularity by about one degree. A comparison of these two points shows a 7 fold decrease from Farewell to King Salmon. Since Farewell station is the one that does not exactly achieve perpendicularity, the true decrease must be greater than or at least equal to 7. From this it is clear that there is a reasonably sharp southern edge of the auroral zone located between 61 and 68 degrees geomagnetic latitude.

The interpretation for zones farther north is considerably less certain since neither College nor Barrow radars approaches perpendicularity very closely. One can consider pairs of range zones in which the propagation angles are equal to avoid becoming involved with the dependence on propagation angle. Picking pairs in this manner and substituting into the equation (4), one can solve for a value of n.

$$\frac{P_1}{P_2} = \left(\frac{R_2}{R_1}\right)^n \tag{4}$$

P_1 = Percent occurrence in zone 1 R_1 = Range to zone 1
P_2 = " " " " 2 R_2 = " " " 2

One would expect values of n lying between 2 and 4, provided that the auroral disturbances occur equally at all ranges. If they occur with increasing frequency at higher ranges, as would be expected for stations south of the maximum of the auroral zone, the values of n will be smaller; conversely, for stations where the frequency of disturbances decreases with increasing range, such as those north of the zone, the value of n would be higher. With the relative coarseness of the range zones, it is only possible to obtain two pair of zones with the same propagation angle from each station. The following table lists these as well as the computed value of n:

TABLE IV

Station	Range zone pairs	n
King Salmon	600 to 700 and 800 to 900	0.88
	500 to 600 and 900 to 1100	1.08
Farewell	600 to 700 and 800 to 900	0
	500 to 600 and 900 to 1100	0.48
College	600 to 700 and 800 to 900	0
	500 to 600 and 900 to 1100	0.08
Barrow	700 to 800 and 800 to 1000	5.3
	600 to 700 and 1000 to 1200	5.2

The conclusion from this calculation is that there is an discernable auroral zone, with a pronounced maximum between 72 and 75 degrees. This maximum falls off fairly sharply on either side with a long wing on the southern edge. These data could certainly be influenced by the side lobe of the antenna,discussed in Chapter II, since an appreciable side lobe contribution would give an erronously high occurrence rate for the higher ranges, and a resulting low value of n. If this is the case, however, it would be nearly equally effective at all stations; in fact, based on the off-perpendicular angle contour plots and echo occurrence plots given by Dyce (1955b), it would appear that this influence would be more effective in reducing the value of n at Barrow than at College!

Only one other piece of evidence exists for a maximum of any type of ionospheric disturbance at this location; it is the latitude of the foci of the disturbance current system as calculated from the magnetic disturbances (Chapman and Bartels, 1940). These two unique points in the current system pass through the field of view of the radar once a day. If they were in any way responsible for the maximum, one would expect to see peaks in the diurnal curve associated with their transit. The single peak of the diurnal curve at Barrow (Figure 18) occurs between 2100 and 2200 local time and does not agree with the time of transit of either focus in the field of view of the Barrow radar.

One is therefore lead to conclude that this maximum or "auroral zone" located quite far north compared to other auroral zones is unique to this interpretation of the radar experiment.

3.3 Distribution of Echoes as a Function of Magnetic Activity

3.3.1 Subdivision of the data by College K value - Since the scalings of the data films are entered on IBM cards, it is a fairly simple, though time consuming, task to punch into an unused column of each card the value of the K index of magnetic activity appropriate to the hour represented by the card. In this study, the three-hourly K values determined by the College Magnetic Observatory were used for all stations because they were more readily available. Subsequently, a comparison of the K values determined by the College Magnetic Observatory and those determined by the Barrow Magnetic Observatory was made. The correlation coefficient between the three-hourly K values at College and Barrow for the month of December, 1958, is 0.89 and between the daily sums of K it is 0.94. Because of this high correlation between the two sets of K indices, it was not deemed necessary to go to the additional work necessary to put the Barrow K indices into all the data cards for the College and Barrow radars. To reduce the amount of card manipulation necessary, this analysis was restricted to the month of December, 1958.

Having the K index in the cards, they can be easily sorted by K value. Then each group can be summed in a fashion identical to that described in the early part of this chapter. Similarly, these sums can also be expressed as percentage activity at any range zone, but the time scale is now in three-hour intervals. Some caution must be exercised in considering these results because often there are only one or two three-hour intervals contributing to the sums; this is especially true for high K values.

Figure 15 shows the per cent activity plotted as a function of range with the range axes shifted to line up with geomagnetic latitude. The curves are for ascending values of K in each of the three-hour periods 9-12, 12-15, and 15-18 UT which are 23-2, 2-5, and 5-8 local time.

In these curves, it is apparent that the activity moves

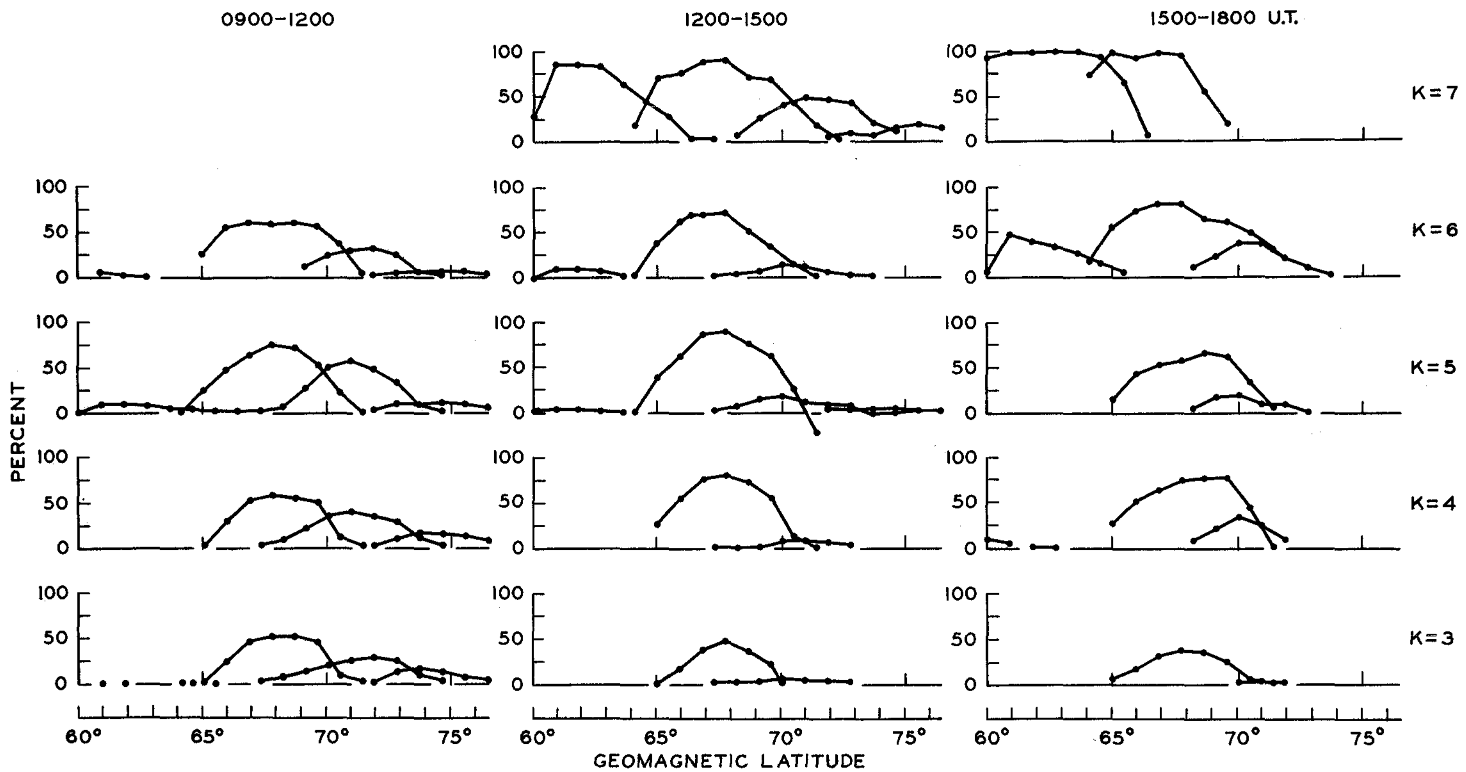

Fig. 15. Auroral zone changes with magnetic activity.

south for increasing values of K, especially late in the evening and early in the morning. In December there were no samples of K = 7 in the 9-12 UT period, so one can only compare the 12-15 and 15-18 UT periods. In these a tendency can be seen for the activity to be higher in the later period, suggesting that the southern movement of the visual auroral zone with increasing K (Elvey et al, 1955) is also time dependent and occurs mainly when the high K is late in the night or in the early morning. For K = 7 in the 15-18 period, the disturbance moves south of the minimum range for King Salmon, that is south of 60 degrees geomagnetic latitude.

The data from Barrow shows virtually no echoes except in the 9-12 UT period. A few minutes of echoes were detected during the other intervals, but because the percentage was less than 1%, no attempt was made to draw the curves on the scale used in Figure 15. Examining the 9-12 UT curves, a tendency exists for the occurrence of echoes to decrease at Barrow and increase at King Salmon with increasing K. This tendency implies that the radar auroral zone shifts south during the high disturbances and not that the maximum remains relatively fixed while the wing to the south expands. Some evidence is found especially in the K = 6 row, that the southern movement is time dependent with the disturbance moving south later in the night.

3.3.2 The influence of absorption on the radar sensitivity - A striking feature of the K = 7 curves is the high percentage of occurrence; it exceeds 90% at all but the extreme ranges at the two southern stations, and in the 15-18 UT period, it is 100%. This very high value means that absorption accompanying the large disturbance (Little & Leinbach, 1958) is at least offset by an increase in the effective back-scattering cross-section of the ionospheric disturbance. A representative value of the absorption on the 30 Mc/s riometer during one of these disturbances is 3 db at vertical incidence. Assuming an auroral echo at 600 km, a uniform absorbing layer, and the radar frequency of 41 Mc/s, the absorption suffered by the radar signal would be about 16 db.

It is difficult to discuss the probability of this large enhancement. No indication of such an enhancement can be inferred from the echoes detected at a much higher frequency (Presnell et al, 1959), but it is dangerous to extrapolate between 40 and 400 Mc/s. It is possible that during the extremely strong disturbances portions of the ionosphere become overdense to the 40 Mc/s signal. An electron density of 2×10^{13} el/m^3 is required to achieve this condition. Current estimates of the electron density in the bright visual auroral forms (Murcray, 1960), are for peak densities of possibly 10^{14} el/m^3, but these densities will exist for of the order of 15 minutes, that is, only during the brightest flashes of the visual aurora. Densities no higher than 5×10^{12} el/m^3 appear more appropriate for periods of the order of 3 hours. If the ionization responsible for the auroral echoes becomes overdense, one would expect an enhancement of the returned signal. Whether or not this enhancement could provide the necessary 16 db is not clear as the scattering mechanism is not understood, especially in this frequency range.

An alternative explanation that would not require this extremely large enhancement of the "reflectivity" is to regard the auroral absorption as not being a continuous layer but as being localized or as having fairly frequent transparent patches. This view is not inconsistent with the absorption measurements made by the riometer since it records the average absorption over the beamwidth of the antenna which is quite large, 60° x 90°. This alternative can be supported by considering the effect of polar cap absorption on the radar.

A daily index of activity can be made from the raw data by computing the average percentage of occurrence in the range zone having the minimum off-perpendicular angle. The results of this computation for the College station are shown in Figure 16 along with the occurrence of polar cap absorption events during 1958 (Reid & Leinbach,1959). Notice that for each such event there is absence of echoes at the beginning of the event, followed by an indication of the exponential recovery in the long duration events. In the cases where the first day does not have a zero, examination of the film

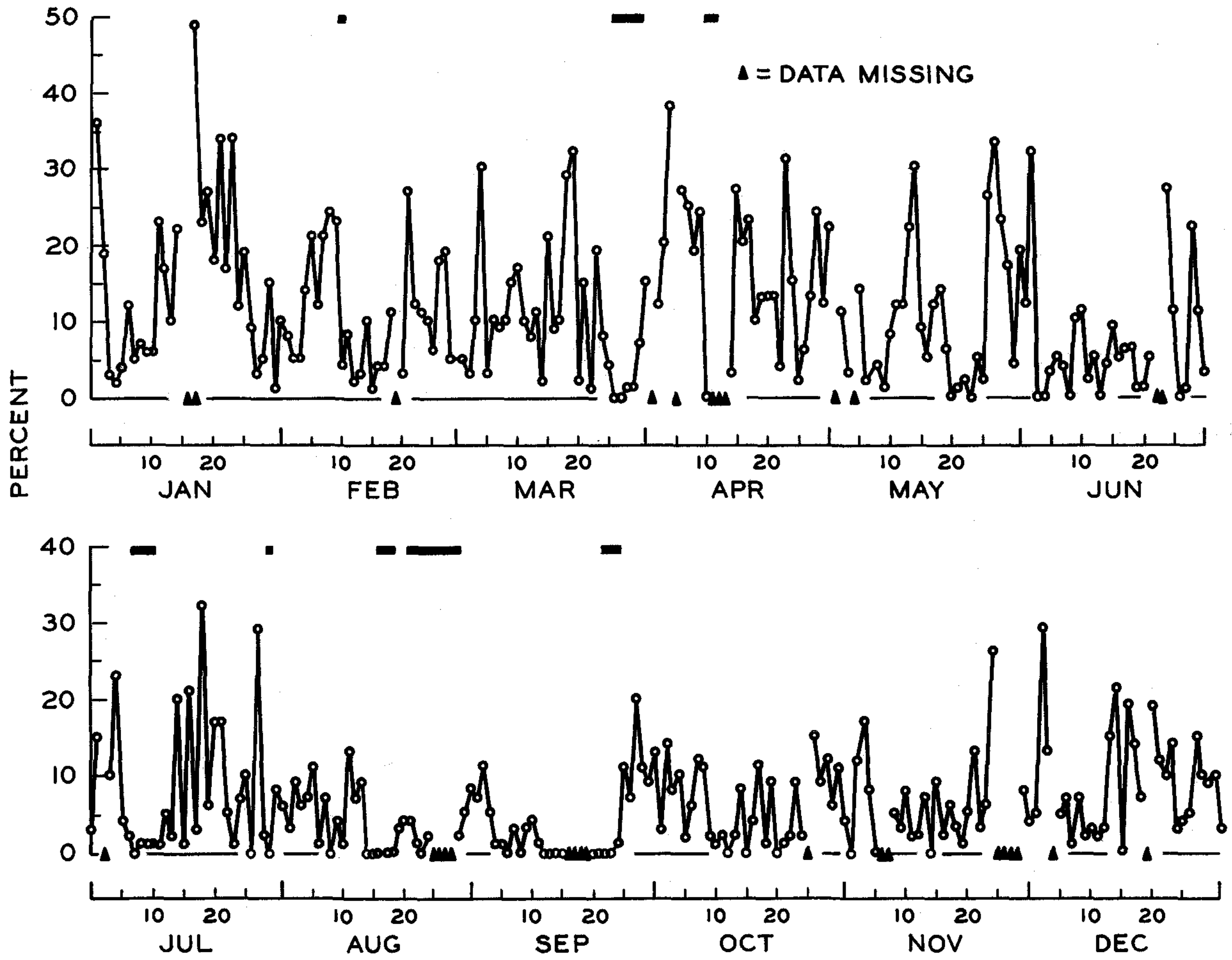

Fig. 16. Annual variation of echoing activity.

shows that the echoes were recorded prior to the onset of the polar cap absorption event. The only other zeros in the data occurred on extremely quiet days as judged by other methods of measurement. Apparently then, the radar sensitivity is reduced markedly by even a very weak polar cap absorption event, but it is not appreciably affected by the auroral absorption accompanying the high latitude geomagnetic disturbances. This difference supports the view that polar cap events are uniform (Reid & Leinbach, 1959) and auroral absorption is patchy (Chapman & Little, 1957).

3.4 Distribution of Echoes in Time

3.4.1 Maxima in the diurnal curves - The echo occurrence sums obtained as described in the preceeding section and converted into percentage occurrences can be plotted against time to give a picture of the diurnal behavior of the auroral echoes. Figure 17 shows the diurnal variations averaged over the whole year in the range zone where the radar ray is most nearly perpendicular to the earth's magnetic field. The time scale is in Universal Time which is 10 hours ahead of local time; hence, local midnight occurs at 1000 UT. Magnetic midnight occurs at the following times for each station:

Barrow	1220 UT
College	1130 UT
Farewell	1140 UT
King Salmon	1150 UT

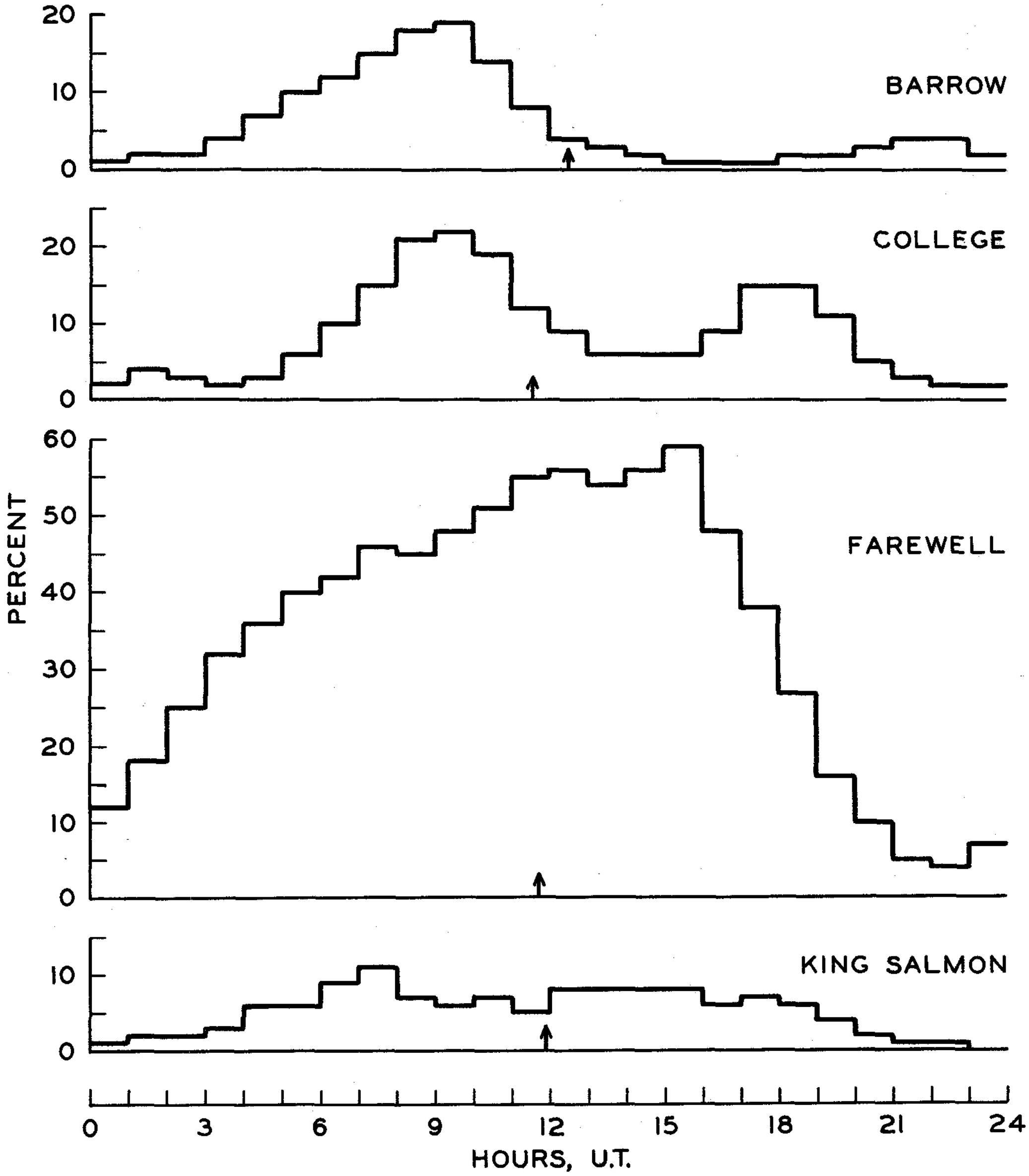

Fig. 17. Diurnal occurrence of auroral echoes.

These times are indicated by small arrows on Figure 17. Considerable variation is found in the diurnal curves from month-to-month, but the general features such as the time of primary & secondary maxima remain substantially the same (see Figure 18). It must be borne in mind while examing these curves that Barrow magnetic midnight is later by approximately one hour.

One of the features in the diurnal curves is the apparent shift in the time of occurrence of the maxima from station to station. In an effort to clarify this effect, the data for the month of June, 1958, was investigated in detail. By using one month rather than an average for the entire year, there is less smoothing of the minor fluctuations. The data were examined by noting the time of occurrence of every maximum in each range zone for all stations; for this purpose a maximum was arbitrarily defined as any hour in which the echo occurrence exceeded that for the two adjacent hours by more than one-tenth of the occurrence percentage. A scatter diagram for these maxima is shown in Figure 19. In this diagram, three echo families can be noted. The first is an echo that tends to occur at 04 UT at all stations. The second is an echo at 10 UT which appears in and north of the visual auroral zone (Davis & Kimball, 1960). The time of occurrence of the third echo family is latitude dependent; it occurs at about 22 UT in the far north around 77 degrees geomagnetic latitude and earlier at lower latitudes. The pattern becomes blurred

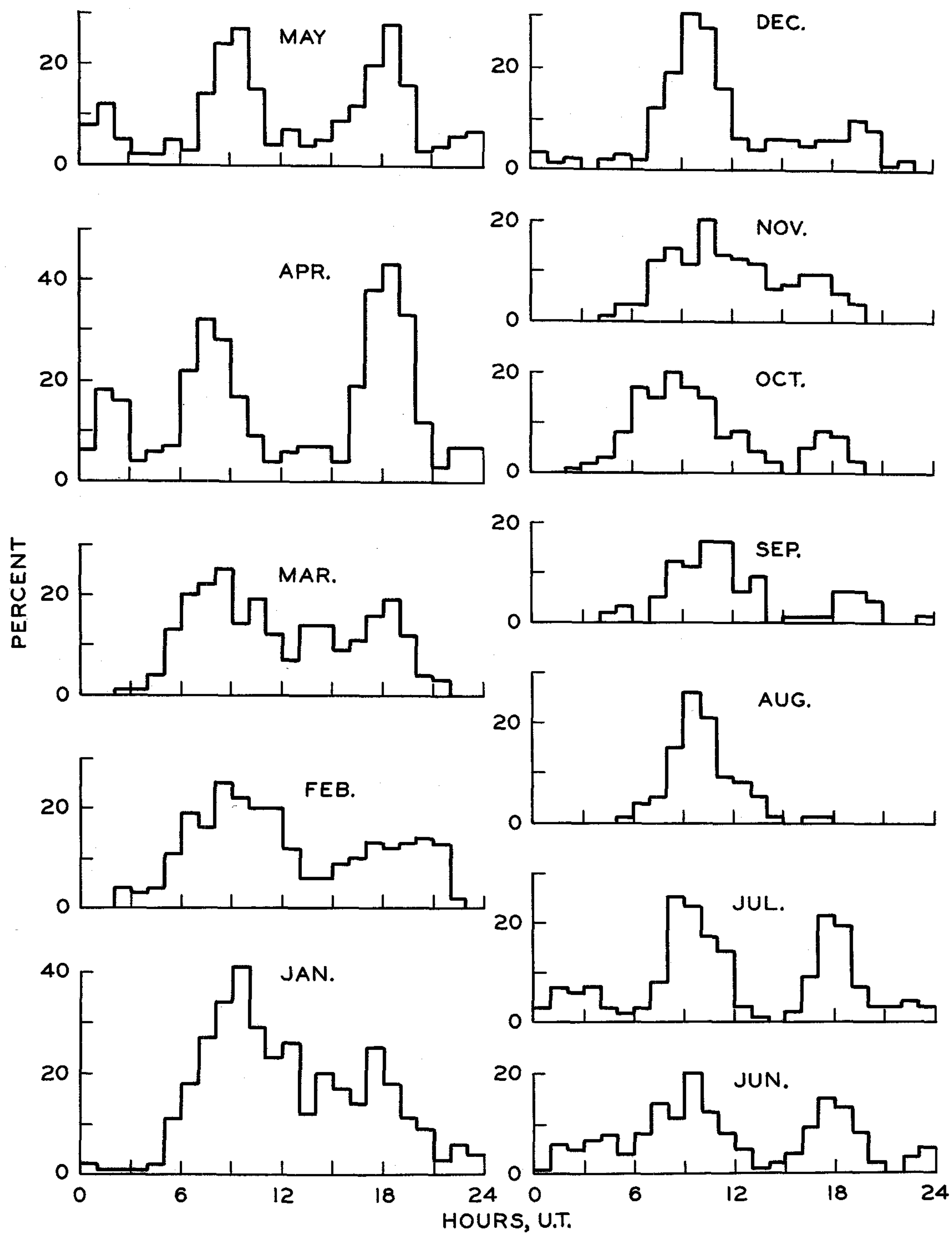

Fig. 18. Diurnal occurrence of auroral echoes for each month at College.

on the southern edge of the visual auroral zone.

The symbols on Figure 19, other than dots, are points determined from work of others published in the open literature (B after Bhattacharyya, 1960; C after Currie et al, 1953; X after Hellgren & Meos, 1952; and T after Presnell et al, 1959). The latitude of these points is estimated since they presumably represent the diurnal curve of echoes at all ranges; they have been put on the curve as being near the zone where the radar ray is most perpendicular to the field unless the author makes a statement indicating some other range. Although a large range of freqeuncies is represented, the points show a fairly close fit to the data from the 41 Mc/s radars.

It is tempting to associate one echo branch with the discrete echoes as identified on the narrow beam UHF radar operated by the Stanford Research Institute at College (Presnell et al, 1959) and the other branch with the diffuse echoes. Presnell reports a tendency, especially at the higher frequencies, for the discrete echo to occur mainly around midnight (10 UT) and the diffuse in the morning (19 UT); this effect is not as obvious at their lowest frequency (216 Mc/s). Visual observations of the echo shape on the 41 Mc/s College radar would support this identification because the nighttime echoes commonly show a sharply defined echo in range, whereas the morning echo is commonly broad and poorly defined, rising slowly from the receiver noise to a

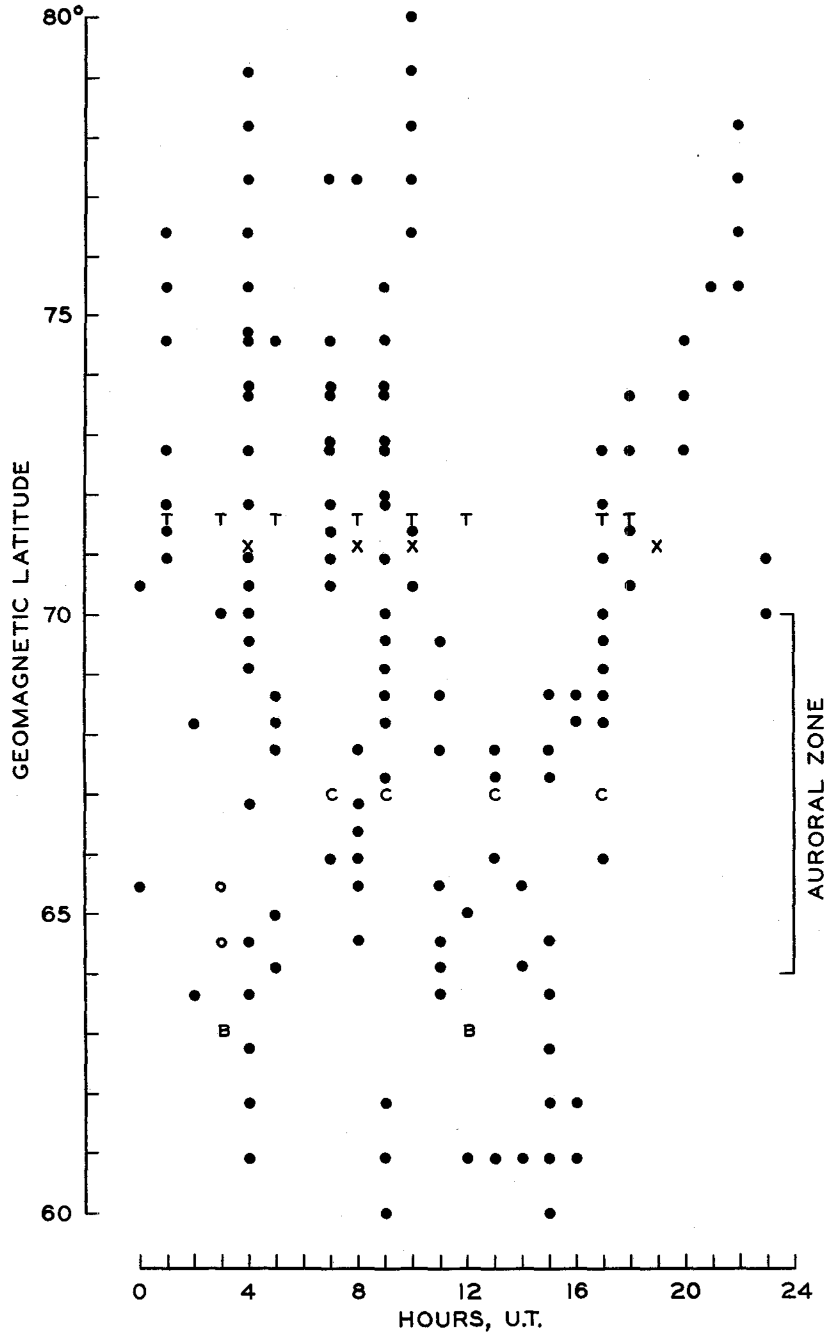

Fig. 19. Latitude of maximum occurrence as a function of time.

broad peak and decending slowly back into the noise. Bates (1961) has compared oblique, sweep-frequency soundings made into the same region as the 41 Mc/s auroral radar observations taken at the College station and has shown a close comparison between the slant-E_s echo and an auroral radar echo. He stated that his slant-E_s echo was primarily a morning phenomenon which commonly disappeared first at the southern end and then farther north later in the day. His statement is in agreement with the latitude dependent branch in Figure 19.

The concept of time of occurrence of high latitude ionospheric disturbances as a function of latitude has been often discussed, especially when the disturbance pattern can be made into a spiral which more-or-less agrees with the classical Störmer (1955) precipitation spirals. Figure 20 shows a polar plot in geomagnetic coordinates of the latitude dependent echo. For this diagram, geomagnetic time was calculated by noting the time difference between local midnight and geomagnetic midnight, rounding this difference off to an even hour, and applying it as a correction factor to local time. This crude method of calculating geomagnetic time was used because the curves do not provide timing accuracy of better than one hour. For comparison, the spiral curves resulting from analyses of other types of high latitude disturbances (M after Malville, 1959; E after Meek, 1955; S after Störmer, 1955; and W after Whitham et al, 1960) are superimposed. This spiral pattern is not be be taken as support for the Störmer

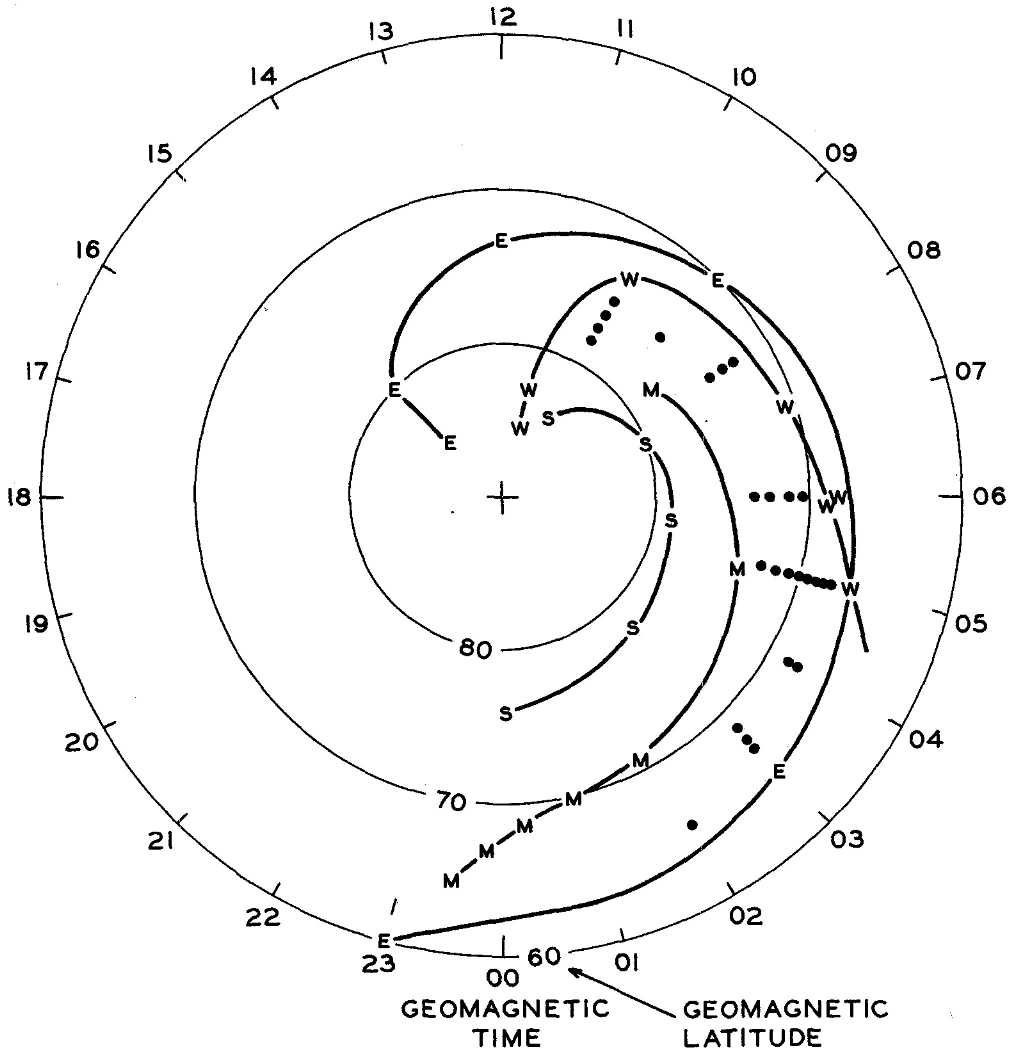

Fig. 20. Spiral patterns and the latitude dependent echo.

precipitation theory which is open to question (Agy, 1960) but rather as for their evidence of a latitude-time dependent disturbance.

3.4.2 Amplitude of the diurnal curves - Unfortunatley, Figure 19 does not give any indication of the relative amplitude of each of these maxima. To display this data, Figure 21 was prepared to show the actual diurnal curves for each individual range zone for each station interleaved in order of increasing geomagnetic latitude. Each curve is drawn with percentage occurrence of auroral echoes on the vertical scale and Universal Time on the horizontal scale; geomagnetic latitude increases from the lower left corner to the upper right corner but is not linearly divided. Care must be exercised when examining these curves; the King Salmon station operated for only a portion of the month of June, and by accident this portion included only very disturbed days, so the curves are noticeably higher than the annual average.

As is expected, the curves show the same features as Figure 19. Some anomalous variations, however, appear in the relative amplitudes. Two adjacent curves from different stations represent observations of nearly the same portions of the sky. The northern station of the pair does not have as wide a coverage in the common range zone (see Figure 1); the portion probed by the northern station is inside the coverage of the southern station for all pairs except College-Barrow. The per cent of the area of detection of the southern

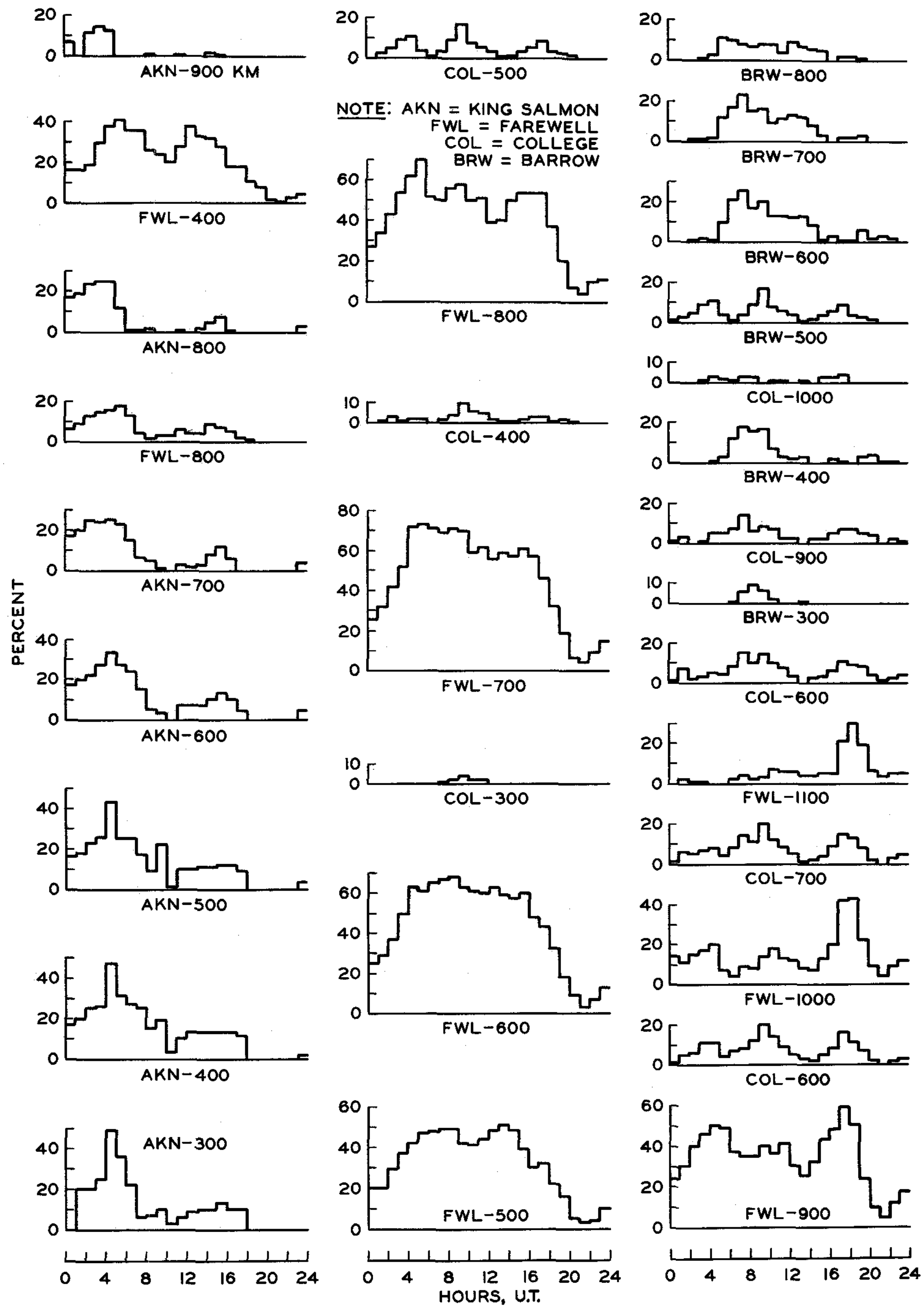

Fig. 21. Diurnal occurrence in individual range zones.

radar covered by the northern radar varies from about 50% in the closest range zone, 300-400 km, of the northern radar to about 65% in the outer most range zone, 1100-1200 km, of the southern radar.

A pair of curves with differences in amplitude but with similar shapes are caused by differences in the overall sensitivity of the two radars to echoes at that specific location. This difference in the sensitivity is caused by the difference in range since the sensitivity is proportional to R^{-n}, where $2 \leq n \leq 4$, and the difference in the propagation angle at the aurora for the different geometries of the two radars. An example is shown in the King Salmon 700-800 km - Farewell 300-400 km pair.

An entirely different situation is present, however, when an adjacent pair of curves not only have different amplitudes but also have different shapes. Examining the right hand column of Figure 21, starting at the bottom, one sees that all the Farewell curves have their principal maximum in the early morning hours, 1700 to 1900 UT, whereas the College curves have their principal maximum around midnight, 0900 to 1000 UT. The effect becomes increasingly more pronounced the farther north the observations are made up to the maximum range for the Farewell station.

The instrumental sensitivity of the two equipments does not vary in this systematic manner over the day. All the experimental parameters, that would affect the overall system sensitivity, are constant in time at both stations. There is a systematic variation in the surface inclination of the magnetic field throughout the day which would affect the magnitude of the propagation angle. In the case of the Farewell-College station pair, the propagation angle is always greater than 90 degrees, so this diurnal change in the magnetic field would act in the direction of improving the sensitivity of both radars. The average diurnal curve of changes in the surface inclination angle of the magnetic field at College for the month of December, 1958, is shown in Figure 22. In this figure, increasing values of the angle act to increase the sensitivity of the radar. Little relation is found between this curve and the diurnal curves of echoing activity; furthermore, no evidence exists that this change in the direction of the magnetic field can cause the discrepancy between the pairs of diurnal curves.

It must be emphasized that the two radars do in fact have different angular fields of view, with the Farewell radar illuminating all of the field of the College radar plus some area on either side of the College field of view. It can then be argued that the Farewell radar sees less activity during the 0900 to 1000 UT peak because of less overall sensitivity but detects more echoes during the 1700-1900 UT peak because the echoes are originating outside of the field of view of the College radar; implying that the disturbances are very restricted in size and are fortuitously located in the non-

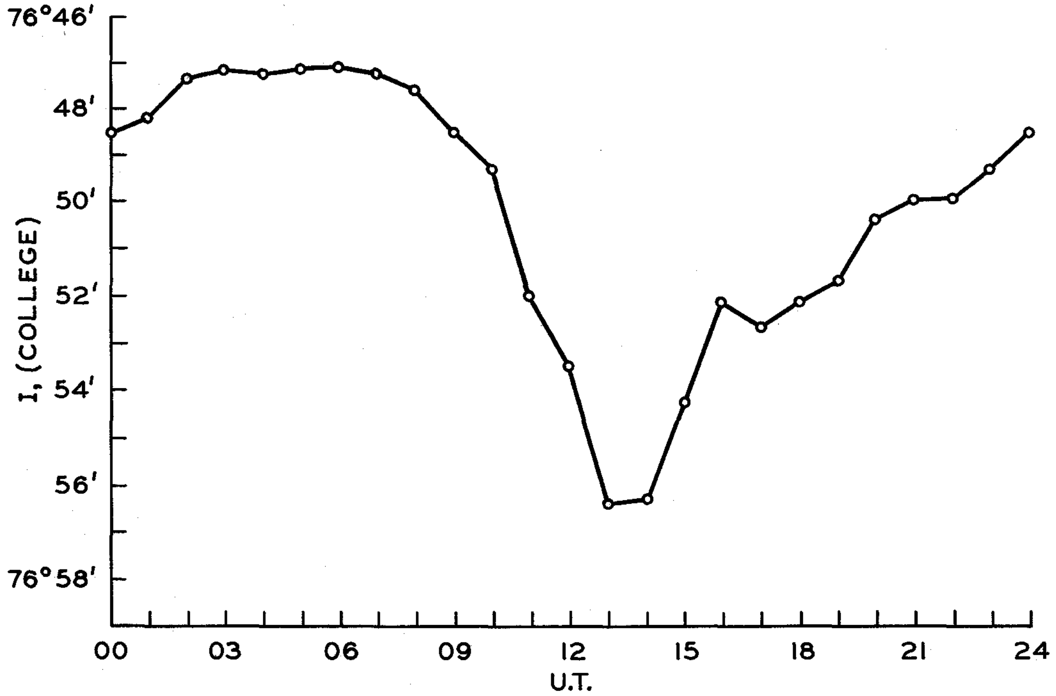

Fig. 22. Diurnal changes in the inclination of the magnetic field at College.

common region viewed only by the Farewell radar. This accurate positioning is rather unlikely and is certainly not supported by the results of Dyce (1955b) which show no such favored regions at any azimuth from College.

The principal remaining parameter that could cause this systematic difference in pairs of curves is a difference in the ionospheric disturbance. If the scattering mechanism active during the 1700 to 1900 UT peak is weak but widespread, it would cause the relative increase in the Farewell curve since a large volume is illuminated by the Farewell radar. The relative maximum in the College curve at 0900 to 1000 UT is in direct opposition to this postulate since any increase in the scattering efficiency to produce an echo on the College radar would also enhance the echo on the Farewell radar; such an enhancement has not been observed.

A closer examination of the parameters for the two stations shows that the College radar is favored over the Farewell radar in the dependence of the radar sensitivity on range because the College radar is approximately 400 km closer to the common scattering region; on the other hand, the Farewell radar is favored over the College radar since it has a propagation angle that is much closer to 90 degrees. Therefore, it appears that the ionospheric disturbances that occur in the morning hours, 1700 to 1900 UT, have a sharper scattering polar diagram, thus throwing the balance of sensitivity to the Farewell radar, while the disturbances occurring near midnight have a broad polar diagram. Enhancement of sensitivity due to the lesser range of the College radar becomes dominant.

*

CHAPTER IV

CONCLUSIONS

At the outset of this experiment it was envisioned that the data would give an understanding of the location and extent of the radar aurora. Empirically this has been done; one can refer to the curves in Chapter III and determine how these disturbances are distributed from station to station. Unfortunately, it is not possible to combine the results directly from each station into a unified picture of the disturbances throughout Alaska.

Certain facts are apparent. There is a radio auroral zone which has a distinct and fairly sharp southern boundary. There is a decrease in the occurrence rate at higher latitudes, implying a northern limit of the auroral zone, but the form of the northern portion of the auroral zone will not be resolved until more detailed knowledge of the role of aspect sensitivity is available. The southern boundary of the auroral zone is a function of the degree of magnetic disturbance with the aurora moving south during higher disturbances. The behavior of the northern edge of the auroral zone as a function of magnetic disturbance was not determined reliably by this study. There is an indication that the auroral activity moves south during high magnetic disturbances, leaving the northern edge of the zone reasonably quiet. This conclusion must be taken with considerable caution; the overall diurnal occurrence curve at higher latitudes has a minimum at the time of most of the large magnetic disturbances during the period that was analyzed.

The principal conclusion from this study is that there appear to be two types of auroral echoes distinguished by a difference in their behavior. Since the data for this report were averaged over periods of one month, or more, some combinations of these two echo types resulted. However, even the averaged diurnal observations show clearly a family of echoes occurs near midnight at all stations and a second family occurs at a progressively later time farther north. The second or latitude-time dependent echo has approximately the same latitude-time relationship as the disturbances reported by other workers. Further, these two types of auroral echoes display different degrees of aspect sensitivity as evidenced by the difference between two stations probing nearly the same region of the ionosphere. The morning echo is more aspect sensitive than the midnight echo. This difference in aspect sensitivity can be interpreted as being due to either (1) a narrower scattering polar diagram of the ionospheric irregularities caused by their greater vertical extent in the morning hours, or (2) distortions in the local magnetic field in the vicinity of the irregularities, causing the midnight echoes to have an apparently broader scattering polar diagram.

In view of this distinction between the two echo types, the data should ideally be divided into two categories before deriving average features like the auroral zone. Unfortunately this is not possible with the data presently available, as in this experiment and analysis the two echoes are identified only by their gross differences in behavior and can not be separated prior to the analysis.

4.1 Recommendations for Further Work

Because of the differences between the two types of echoes found in this study, it is not surprising that other workers in the field find different results depending on the relative importance of each echo type in their data. It is suggested, therefore, that an experiment be conducted at frequencies in the low VHF band which will separate the echoes according to type as they are being recorded. When this distinction by type has been established it is then necessary to determine the aspect sensitivity or scattering polar diagram of the ionospheric irregularities. It is quite possible that the determination of the scattering polar diagram will further help to distinguish between the two types of echo. With this information, one should be able to correct the curves given in this report so that they would represent the relative degree of ionospheric disturbances.

*

ACKNOWLEDGEMENTS

The author wishes to express his thanks to the members of his supervising committee; Dr. W. Flock, Dr. G. C. Rumi, Dr. C. G. Little, Dr. L. Owren and Dr. A. M. Bork for their many helpful comments and suggestions throughout the course of this work.

The installation and operation of the equipments during the International Geophysical Year was supported by the National Science Foundation. Operations at several stations in Alaska were made possible by the support of the Federal Aviation Administration who provided heated buildings and electrical power at King Salmon, Farewell, and Kotzebue. The operation at Barrow, Alaska, was similarly supported by the Arctic Research Laboratory. The location of a station at Unalaska, Alaska, was made possible through the courtesy of the Commandant, 17th Naval District, Alaskan Sea Frontier. Scaling and analysis of the data were supported by the National Science Foundation.

*

REFERENCES

Agy, V., Spiral Patterns in Geophysics, J. Atmospheric and Terrest. Phys., 19, 136-140, 1960.

Aspinall, A., and G. S. Hawkins, Radio Echo Reflections from the Aurora Borealis, J. British Astronomical Assoc., 60, 130-135, 1950.

Bates, H. F., The Slant E_s Echo--A High Frequency Auroral Echo, J. Geophys. Research, 66, 447-454, 1961.

Bhattacharyya, B. K., Correlation Studies of Radio-Aurora, Magnetic, and Earth Current Disturbances, Canadian J. Phys. 38, 624-637, 1960.

Booker, H. G., C. W. Gartlein and B. Nichols, Interpretation of Radio Reflections from the Aurora, J. Geophys. Research, 60, 1-22, 1955.

Booker, H. G., A Theory of Scattering by Non-isotropic Irregularities with Application to Radar Reflections from the Aurora, J. Atmospheric and Terrest. Phys., 8, 204-221, 1956.

Bullough, K. and T. R. Kaiser, Radio Reflections from Aurora--II, J. Atmospheric and Terrest. Phys., 6, 198-214, 1955.

Chapman, S. and J. Bartels, Geomagnetism, Vol. I, London, Oxford University Press, 1940, p. 310.

Chapman, S. and C. G. Little, The Nondeviative Absorption of High-Frequency Radio Waves in Auroral Latitudes, J. Atmospheric and Terrest. Phys., 10, 20-31, 1957.

Currie, B. W., P. A. Forsyth, F. E. Vawter, Radio Reflections from Aurora, J. Geophys. Research, 58, 179-200, 1953.

Davis, T. N. and D. S. Kimball, Incidence of Auroras and their North-South Motions in the Northern Auroral Zone, Geophysical Institute Scientific Report No. UAG-R100, Jan., 1960.

Dyce, R. B., Auroral Echoes Observed North of the Auroral Zone on 51.9 Mc/s., J. Geophys. Research, 60, 317-323, 1955a.

Dyce, R. B., Communication Aspects of VHF Auroral Reflections, School of Electrical Engineering, Cornell Univ. Research Report EE 249, June 1955b.

Elvey, C. T., F. H. Leinbach, J. Hessler, J. Noxon, Preliminary Studies of the Distribution of Auroras in Alaska, Trans. Am. Geophys. Union, 36, 390-394, 1955.

Gadsden, M., Studies of the Upper Atmosphere from Invercargill, New Zealand, Part III--Radar Echoes and Visual Aurora, Annales de Geophysique, 15, 403-411, 1959.

Gartlein, C. W., G. Sprague, R. C. Wagg, 41 Mc/s IGY Auroral Radar at Ithaca, New York, J. Geophys. Research, 65, 2255-2259, 1960.

Harang, L., The Aurora, John Wiley & Sons, Inc., 1951, p. 41.

Harang, L. and B. Landmark, Radio Echoes Observed During Aurorae and Geomagnetic Storms using 35 and 74 Mc/s Waves simultaneously, J. Atmospheric and Terrest. Phys., 4, 322-338, 1954.

Hellgren, G., and J. Meos, Localization of Aurorae with 10m High Power Radar Technique, using a Rotating Antenna., Tellus, 4, 249-261, 1952.

Herlofson, N., Interpretation of Radio Echoes from Polar Aurora, Nature, 160, 867-868, 1947.

Howells, I. D., On the Spectrum of Electron Density Produced by Turbulence in the Ionosphere in the Presence of a Magnetic Field, J. Geophys. Research 64, 2198-2199, 1959.

Leonard, R. S., Measurement of Effective Auroral Target Area at 41 Mc/s, Paper presented at Alaska Division Am. Assoc. for the Advancement of Science Meeting, Sept. 1958.

Little, C. G. and F. H. Leinbach, Some Measurements of High-Latitude Ionospheric Absorption using Extraterrestrial Radio Waves, Proc. IRE, 46, 334-348, 1958.

Lovell, A.C.B., J. A. Clegg, C.D. Ellyett, Radio Echoes from the Aurora Borealis, Nature, 160, 372, 1947.

Lyon, G. F., The Association of Visible Auroral Forms with Radar Echoes, Canadian J. Phys. 38, 385-389, 1960.

Malville, J. M., Antarctic Auroral Observations, Ellsworth Station, 1957, J. Geophys. Research, 64, 1389-1393, 1959.

Meek, J. H., The Location and Shape of the Auroral Zone, J. Atmospheric and Terrest. Phys., 6, 313-321, 1955.

Moore, R. K., A VHF Propagation Phenomenon Associated with Aurora, J. Geophys. Research, 56, 97-106, 1951.

Murcray, W. B., Correlation Between the Luminous Aurora and some other Phenomena., Paper Presented at the Am. Geophysical Union Meeting, 1960.

Owren, L., High Latitude Radio Aurora, Proceedings of the XIII General Assembly of U.R.S.I. Commission III, Sept. 1960, (To be published).

Presnell, R. I., R. L. Leadabrand, A. M. Peterson, R. B. Dyce, J. C. Schlofohm, and M. R. Berg., VHF and UHF Radar Observations of the Aurora at College, Alaska, J. Geophys. Research 64, 1179-1190, 1959.

Reid, G.C. and F. H. Leinbach, Low Energy Cosmic Ray Events Associated with Solar Flares, J. Geophys. Research, 64, 1801-1805, 1959.

Seed, T. J., V.H.F. Observations on the Aurora Australis, J. Geophys. Research, 63, 517-526, 1958.

Störmer, C., Photographische Hohenmessungen und Spectra des grossen Nordlichtes vom 25. bis 26, January, 1938, Naturwiss 26, 633-638, 1938.

Störmer, C., The Polar Aurora, London, Oxford University Press, 1955, p. 312.

Uda, S. and Y. Mushiake, Yagi-Uda Antenna, Sendai, Japan, Sasaki Printing and Publishing Co. Ltd., 1954, p. 156.

Unwin, R. S., The Geometry of Auroral Ionization, J. Geophys. Research 63, 501-506, 1958.

Unwin, R. S., Studies of the Upper Atmosphere from Invercargill, New Zealand, Part I, Characteristics of Auroral Radar Echoes at 55 Mc/sec., Annales de Geophysique 15, 377-394, 1959.

Vestine, E. H., The Geographic Incidence of Aurora and Magnetic Disturbance, Northern Hemisphere, Terrestrial Magnetism and Atmospheric Electricity, 49, 77-102, 1944.

Whitham, K., E. I. Loomer, and E. R. Niblett, The Latitudinal Distribution of Magnetic Activity in Canada, J. Geophys. Research 65, 3961-3974, 1960.

*